Geospatial Water Balancing for the South Florida Water Management District

by

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To my Mom and Dad, who have supported me in everything I do.

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Geospatial Water Balancing for the South Florida Water Management District

By

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The University of Texas at Austin, 2005

SUPERVISOR: David R. Maidment

The main objective of this thesis is to create a methodology for calculation the simple water balance proposed by Ron Mireau automatically and within a GIS framework. In the initial part of this project a data model was developed to describe the spatial features of the hydrologic system within the SFWMD. In conjunction with the SFWMD, PBS&J, and CRWR, an Arc Hydro Enterprise Database (AHED) was developed and implemented in a geodatabase design. The AHED is an extension of the Arc Hydro data model. This thesis looked at ways to describe the movement of water through the SFWMD using the defined geodatabase features in the AHED. To describe the movement of water in the SFWMD two new terms were defined: water control unit and water control catchment. A water control unit can be considered the operationally significant portion of the water control unit network, the water bodies control by the SFWMD. A water control catchment is defined as the extent of land surface area that drains into a water control unit

The Hydrologic Flux Coupler is an excellent approach to automating the geospatial water balance method. Once the links between the documented fluxes and flows are established in the Hydrologic Flux Coupler the only additional requirement is to add time series information into the Timeseries table, in the correct format. The data collection time and computation time of the Hydrologic Flux Coupler is reduces compared to the amount of time required to create an Excel spreadsheet. In particular, the Hydrologic Flux Coupler decreases the amount of time for creating visualizations of the time series information.

In addition to the development of the geospatial water balance, an additional analysis of the sensitivity of the geospatial water balance was preformed on the C41-A-North water control unit and catchment for an entire year, November 1, 2002 to October 31, 2003. The results of the data evaluation over the C41-A-North produces conclusions in four areas of interest: rainfall; evaporation and evapotranspiration; calculation of Q_{TRANS}; and estimation of water surface area.

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1 Introduction

1.1 Background

The South Florida Water Management District (SFWMD) is one of five water management districts within the state of Florida; and is located along the southern tip of Florida, covering nearly 17,000 square miles. The mission of the SFWMD is to provide flood protection, water supply, and water quality protection to the nearly six million residents who live and work in the area, as well as manage and restore the ecosystems to a more natural level within the region (Redfield et al., 2004).

A water management team comprised of four water managers makes the daily decisions of what structures to control and how to move water through the SFWMD while meeting all of the regulatory requirements regarding water quantity and quality. Water management decisions are based on regulations, codes and water management goals set by the SFWMD, and the state of Florida. Using their knowledge of the state of the hydrologic system, the observed water levels and flows in the system, the water managers develop a water management strategy that is implemented by the Operations and Maintenance operators and field personnel.

1.2 Problem Statement

Water managers in the South Florida Water Management District are tasked with the daily development of water management strategies for the SFWMD based on the current state of the water system, regulatory requirements, and forecasted weather patterns. The state of the SFWMD operated water system is comprised of SFWMD controlled canals and lakes, is based on water observations throughout the SFWMD. (Amadori, 2004) The water system operated by the SFWMD includes 1800 miles of canals and levees; 25 pump stations; 200 major control structures, such as spillways; and 2000 smaller control structures, Figure 1. (SFWMD, 2005a) However, the sheer size of the SFWMD, over 17,000 mi^2, is too large for detailed development, thus a smaller area of interest, called the Three Lakes test area, is studied in detail, with particular attention being paid to the

C41-A-North water control catchment, Figure 2. The Three Lakes test area includes Lakes Okeechobee, Istokpoga, and Kissimmee, and was selected based on the inclusion of these large lakes, minimal to no tidal effects, watersheds of significant size, and two types of hydraulic flow systems: multiple flow paths and single flow paths.

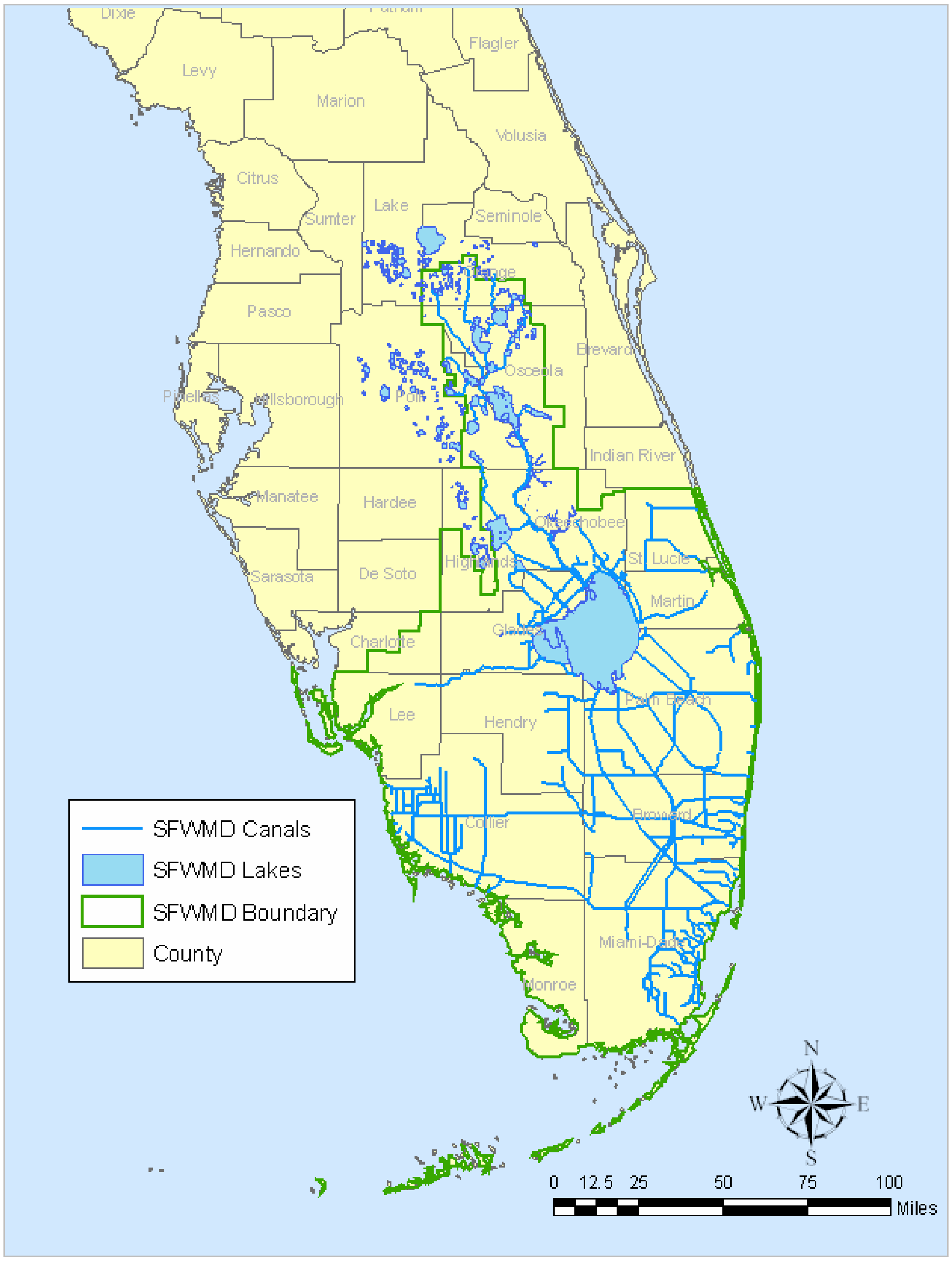


Figure 1: South Florida Water Management District with lakes and canals operated by SFWMD

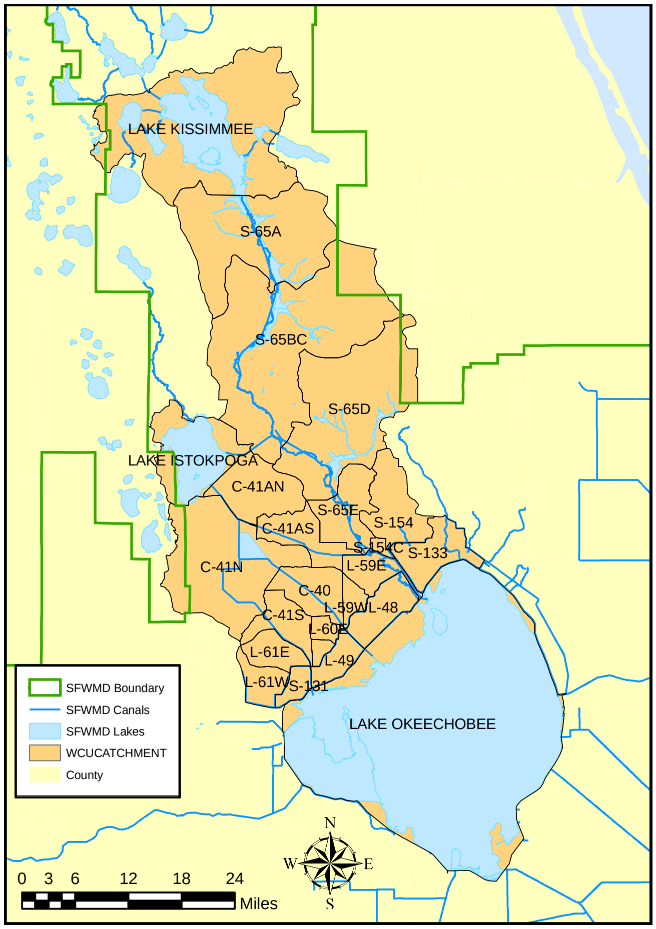


Figure 2 Three Lakes Test Area for development of Operations Decision Support System

The operations system is monitored by a sophisticated SCADA (Supervisory Control and Data Acquisition) monitoring system. The system presently measures over 3000 parameters on a real-time basis, with an anticipated increase in the number of sensors from the present level for 300 sensors to over 7000 measured parameters by 2020 (Stewart, 2004). However, the drawback in the existing real-time measurement system is it only provides answers to how the current state of the system is limited; it does not provide an estimate of how much capacity is available in the system. Nor does the system have the capability to predict the state of the system in the near future; for example, what the state of system will be in several hours from the present observations. (Mireau, 2003)

1.3 Objectives

The objectives of this thesis are two-fold; firstly create a geospatial water balance approach for estimating the hydrologic state of the system as laid out in Ron Mireau's communication titled Operational Water Budget Accounting, dated March 1, 2004, Appendix A. As Mireau states 'the simple water balance is intended to provide a water manager with tools to evaluate and determine the index of the hydrologic system in a particular water control unit'. Although the task is currently being done by water managers at the SFWMD, it is generally done on a more informal level than the proposed water balance approach. The present method of water balancing is based on rainfall forecasts, observed water levels, observed flow rates, observed flow directions, and a review of previous conditions. (Mireau, 2004) To promote more scientific water management decisions, linking the different components of the hydrologic cycle together, a geospatial water balance method is proposed.

The second objective of this thesis is to evaluate the applicability of the geospatial water balance to the south Florida region and evaluate alternative data sources for input into the geospatial water balance. There are many different types of data sources for the fluxes moving into and out of a basin, these fluxes include: rainfall, evaporation, evapotranspiration, and infiltration. There are many ways of measuring these fluxes; for example, rainfall flux is measured using rain gages as well as NEXRAD rainfall estimates. Both data types are potential input for a water balance model; however, there are accuracy and data management constraints with both data types. Evaporation and evapotranspiration values are more difficult to directly measure than precipitation, thus are measured at fewer points in the SFWMD than precipitation. (Dingman, 2002)

1.4 Overview

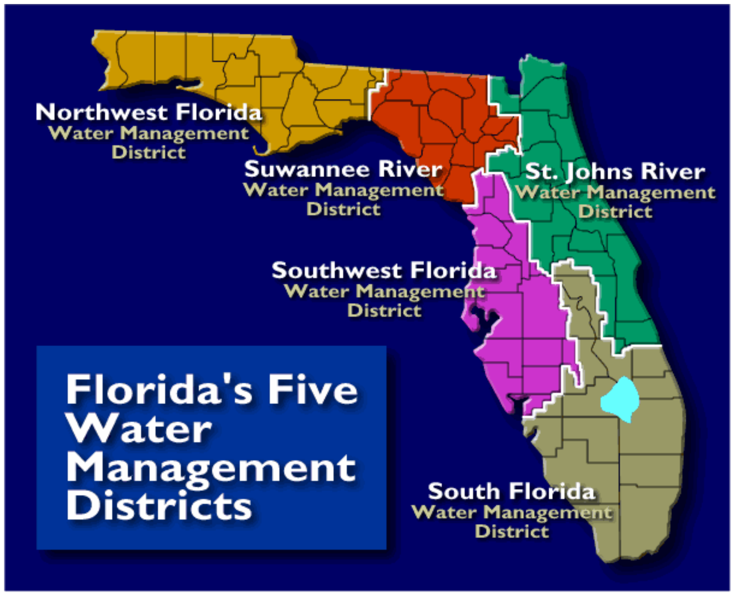
This thesis is divided into six different Chapters. In the first Chapter, the Introduction, the scope of the problem is defined and the motivation for the project is described. In the second Chapter, Background, a general introduction of the SFWMD region is presented, the types of measurement and estimation techniques for the fluxes and flows used in the geospatial water balance are presented. Additionally, in the second part of Chapter 2 the initial development of the ArcGIS Operational Decision Support System feature data set for the Enhanced Arc Hydro geodatabase for the SFWMD is introduced. In the third chapter, Methodology, the geospatial water balance is presented and the techniques used to calculate the inputs and measurements of the geospatial water balance are presented. The fourth chapter, Results, presents the results of analysis for the geospatial water balance and discusses the impact of different inputs to the geospatial water balance. A specific area of interest is examined, the C41-A-North water control unit in the Three Lakes test region. The fifth chapter of the thesis, Conclusions, provides a summary of the conclusions drawn from the results and methodology described in the previous two Chapters. The thesis is concluded with Recommendations, which draws upon the conclusions and results presented previously to assist subsequent research on the subject as well as suggested areas of work for the continued development of the water balancing techniques within ArcGIS.

2 Background

2.1 South Florida Water Management District

Water development in South Florida was significantly impacted by the actions of the United States Congress Flood Control Act of 1948, which ordered the U.S. Army Corps of Engineers to design and build an enormous flood control project to protect agricultural land and newly created urban areas in Southern Florida. (Purdum, 2002) To maintain and operate the newly created flood control project, the Central and Southern Florida Flood Control District was created in 1949. (Redfield et al., 2004) Construction of major water control works continued into the 1960s, including the construction of the Kissimmee Canal then began in 1962. Major waterway construction was halted in 1971 by President Nixon due to public outcry. (Purdum, 2002)

Attitudes towards water in Florida changed in the early 1970's; Florida experienced its worst recorded drought, to date, in 1970-71 (Purdum, 2002). In 1972 the Florida legislature passed the Florida Water Resources Act (Chapter 373) creating five water management districts, Figure 3, with expanded responsibilities which included water resources management and environmental protection, as well as, continuing flood control protection. (SFWMD, 2005a) The five water management districts were created based on surface water flow direction rather than political boundaries; this was designed to ensure water management decisions were not made for purely political reasons (Purdum, 2002). The Central and Southern Florida Flood Control District was renamed the South Florida Water Management District (SFWMD). The SFWMD and the other four water management districts are overseen by the state of Florida's Department of Environmental Protection and funded by property taxes levied in each water management district. (SFWMD, 2005a)



Source: South Florida Water Management District

Figure 3: Five Water Management Districts within the state of Florida

As a result of the U.S. Army Corps of Engineers project, the Central and Southern Florida Flood Control District was charged with operating 1,800 miles of canals and levees across southern Florida. To manage the movement of water on a daily basis the SFWMD employs a water management team whose role it is to understand the state of the water system in the SFWMD and to develop water management strategies meeting the main objectives of the SFWMD: flood control, water supply and environmental protection. (PBS&J, 2004a)

2.1.1 Climate of Southern Florida

The climate of the Three Lakes test area is representative of the climate of southern and central Florida. Long term average precipitation rates within the SFWMD are reported for fourteen rain areas. The fourteen rain areas were created to facilitate the operations of Operations and Maintenance Department (OMD) of the SFWMD. The rain areas are used for many purposes and by a multitude of personnel, which include District meteorologists, hydrologists, operators, and planners, Figure 4. On average, the SFWMD receives 52.8 inches of rain per year over the entire SFWMD; however, the average rainfall measured in the three rain areas from 1915 to 1985 that describe the Three Lakes region receive an average of 44.45 inches, 45.97 inches, and 50.09 inches per year for rain areas Lower Kissimmee, Lake Okeechobee, and Upper Kissimmee. The rain areas are used on a daily basis by the District meteorologists to forecast daily rainfall amounts for each rain area, in inches per day in the format shown in Table 1, which shows the estimated precipitation for February 28, 2005. In addition to the fourteen rain areas, there are over 100 rainfall gages that record precipitation throughout the SFWMD. The area of the fourteen OMD rainfall areas is assumed, for operational purposes, to be small enough for rainfall characteristics to be statistically homogeneous within a given rain area. (Ali and Abtew, 1999) This assumption may not hold true for rainfall data on a smaller temporal scale than daily data. Ali and Abtew's statement of homogenous rainfall characteristics over rainfall areas was applied to rainfall data on a monthly, seasonal, and annual basis and did not look at rainfall data on a smaller temporal scale than monthly.

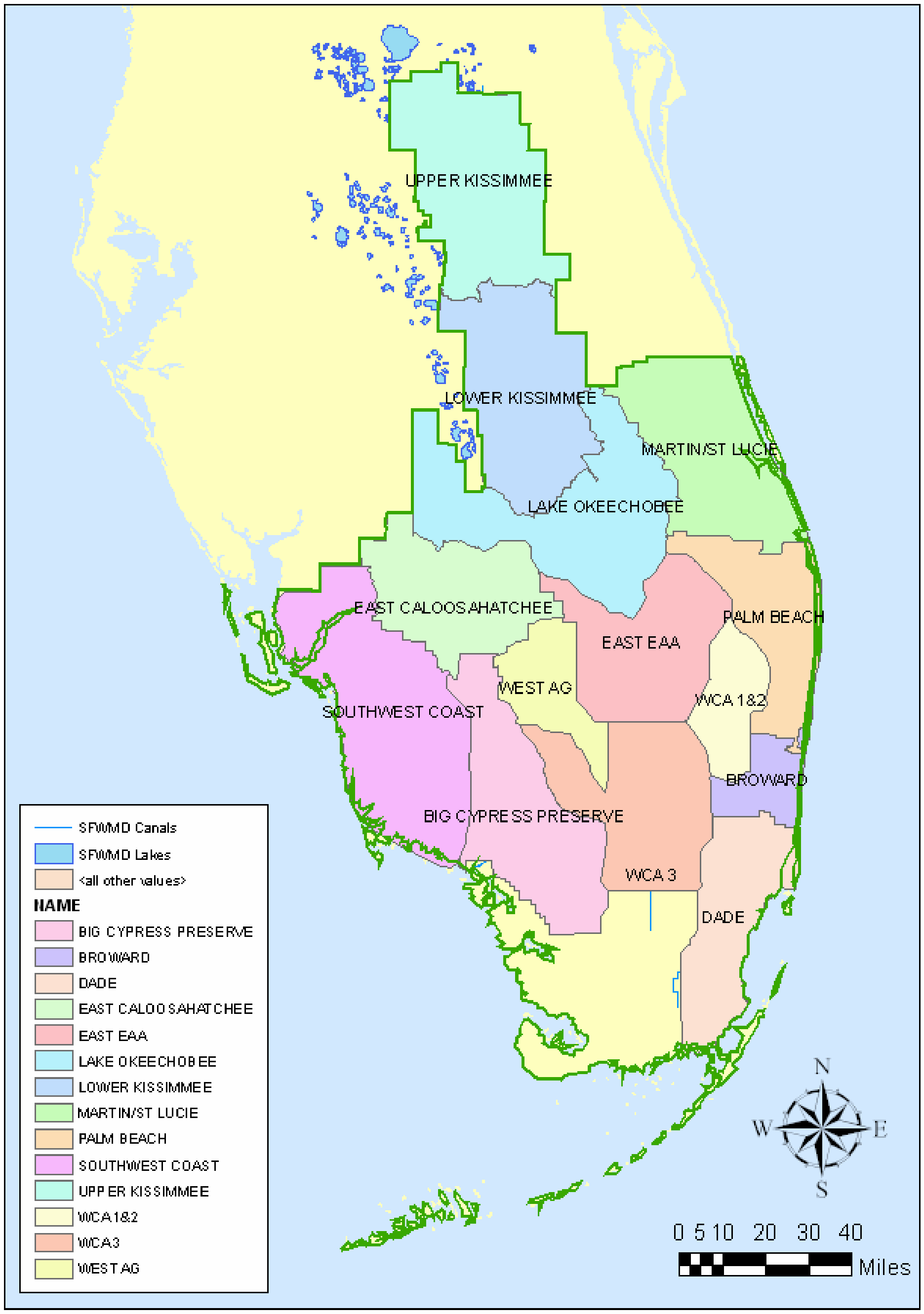


Figure 4 Fourteen Rain Areas covering South Florida Water Management District

Table 1 Rain Area rainfall estimates for South Florida Water Management District for Monday 2/28/2005

Quantitative Precipitation Forecast	24Hr Begin 7AM Mon	Local Max	24Hr Begin 7AM Tue
Upper Kissimmee	0.0	0"	0.0
Lower Kissimmee	0.0	0"	0.0
Lake Okeechobee	0.0	<1"	0.0
Eastern Agricultural Areas	0.01	<1"	0.0
Western Agricultural Areas	0.01	<1"	0.0
Conservation Areas 1&2	0.01	<1"	0.0
Conservation Area 3	0.05	<1"	0.0
Martin/St Lucie Counties	0.0	0"	0.0
Eastern Palm Beach County	0.01	<1"	0.0
Eastern Broward County	0.05	<1"	0.0
Eastern Miami-Dade County	0.10	<1"	0.0
East Caloosahatchee	0.0	<1"	0.0
Big Cypress Preserve	0.01	<1"	0.0
Southwest Coast	0.0	<1"	0.0
District Overall	0.01	-	0.00

The water cycle in southern Florida is driven mainly by precipitation (Ali and Abtew, 1999). Thus it is important to understand the distribution of rainfall over the region. In the SFWMD, the wettest month is historically June and the driest month is historically December, Figure 5. The wet season in the SFWMD is from June through October, which accounts for 66 percent of the annual total rainfall, conversely 35 percent of the annual total rainfall falls in the dry season, from November through May. The majority of the precipitation associated with the wet season is associated with local convective showers or thunderstorms, with 57 percent of rainfall falling on undisturbed sea breeze days, with an occasional tropical storm passing through the SFWMD at intermittent time periods (Abtew et al., 2004). Precipitation is not associated with orthographic effects, due the limited change in topography of Florida. The highest point in the SFWMD is approximately 210 feet above mean sea level, based on the National Elevation Dataset information, the lowest point in the SFWMD is sea level.

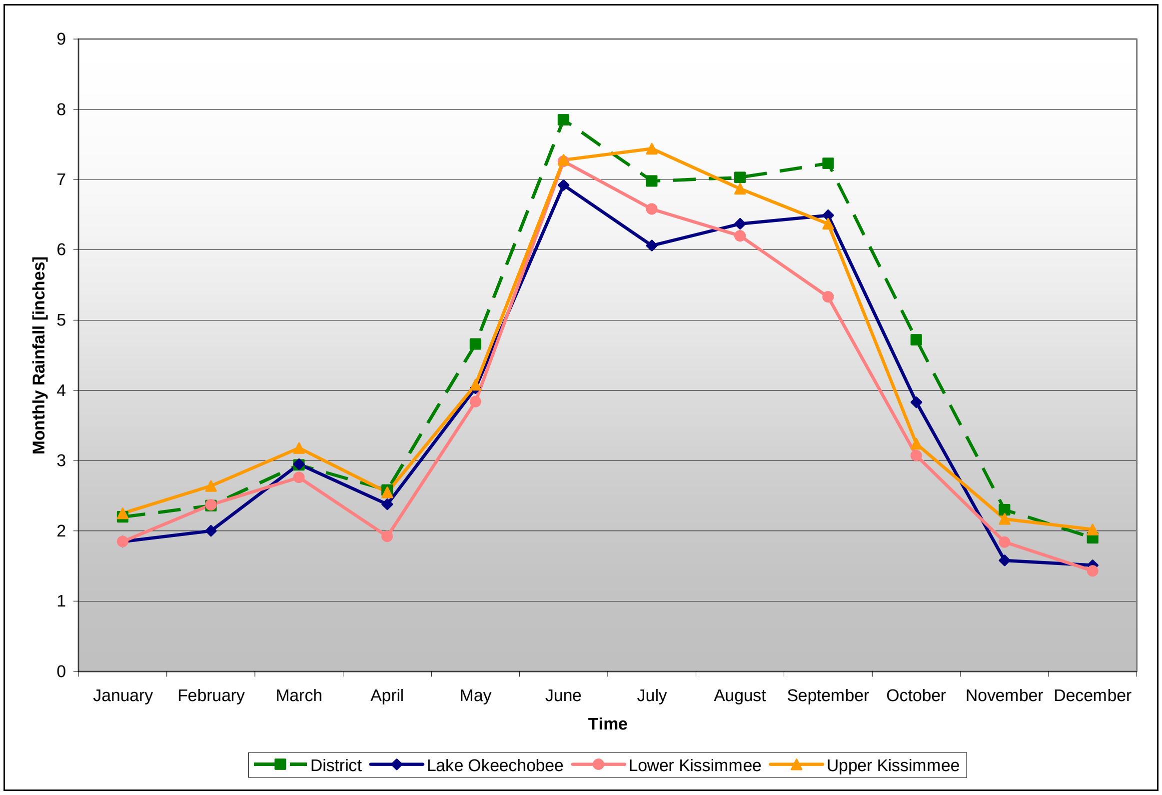


Figure 5 Historic rainfall average values for the SFWMD and three rainfall rain areas (Based on data from Ali and Abtew, 1999)

The second parameter that drives the water balance in the SFWMD is evaporation or evapotranspiration. For wetlands and areas that are wet year-round the average evapotranspiration rate per year ranges from 48 inches per year in the northern part of the district to 54 inches per year in the Everglades. Evaporation and evapotranspiration are functions of solar radiation, air temperature, wind speed, vapor pressure deficit, atmospheric pressure, and physical characteristics of the surrounding environment (Abtew et al., 2003). In southern Florida, wind speed is generally low, humidity is high, and rainfall is high, therefore variations in evapotranspiration are based on variations in solar radiation (Abtew et al., 2004). As reported in Abtew et al., 2003 based on a one-year lysimeter test, the annual evapotranspiration from a freshwater marsh is approximately 131.7 cm [51.9 inches]. Based on water budget data collected from 1940 to 1946 the average annual Lake Okeechobee evaporation rate was reported as 132 cm [52.0 inches]. Using different methodology again, a Bowen-ratio energy balance method in southern Florida reported an average annual evapotranspiration rate of 122.2 cm [48.1 inches]; however several sites in the study were dry for a part of the study year. The lack of evaporative moisture in the soil for part of the year is a limiting factor in evapotranspiration compared to the potential evapotranspiration rate. There are only slight seasonal variations in potential evapotranspiration across the SFWMD compared to variations in rainfall. Monthly variations in potential evapotranspiration, over the entire SFWMD, range from a low of 2.36 mm/day [0.09 inches/day] in December to a high of 4.63 mm/day [0.18 inches/day] in May. Monthly variation in potential evapotranspiration over the entire SFWMD, as reported in Abtew et al., 2003, is shown in Figure 6. The present method to estimate potential evapotranspiration for each rainfall area is to find the closest site that measures potential evapotranspiration and assume that the potential evapotranspiration at that site is equivalent to the potential evapotranspiration of the rainfall rain area. (Abtew, 2004)

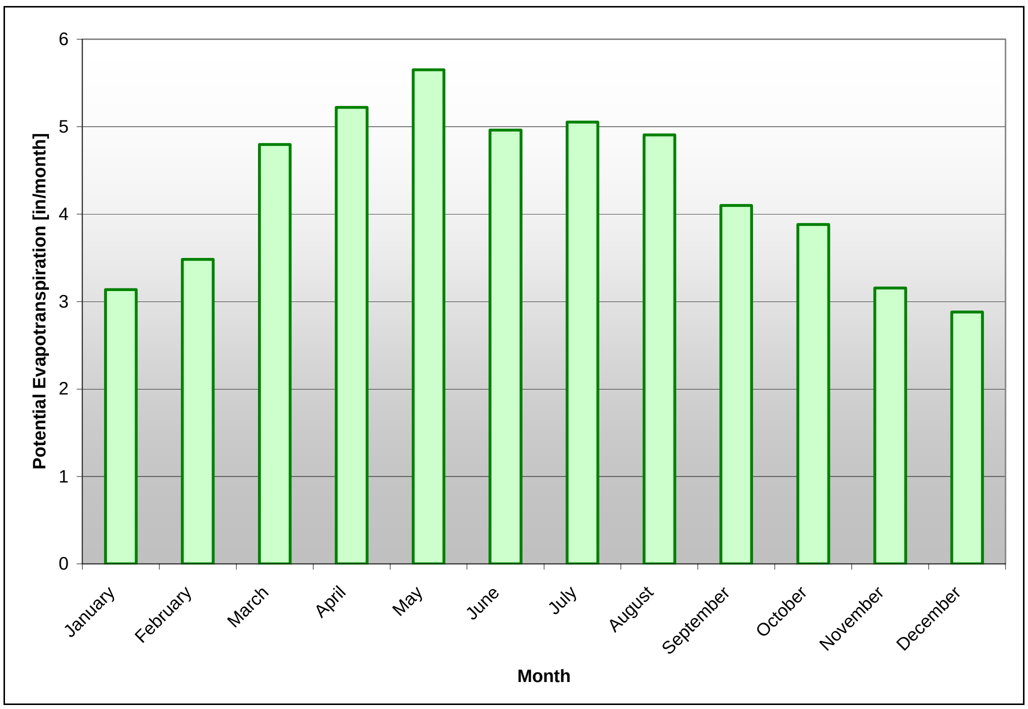


Figure 6 Monthly averages of potential evapotranspiration for the entire SFWMD

The most commonly measured evapotranspiration rate in the SFWMD is potential evapotranspiration which is defined as the evapotranspiration that would occur from an area where moisture is not limiting the rate of evapotranspiration. The actual rate of evapotranspiration decreases as the soils dry out. (Chow et al., 1988) However open water systems and wetland systems evaporate water at the potential evapotranspiration rate. (Abtew et al., 2003) In the water year 2004, which runs from May 1, 2003 to April 30, 2004 the estimated potential evapotranspiration for Lake Okeechobee, Upper Kissimmee, and the Lower Kissimmee rainfall areas, was 51.1 inches, 52.7 inches, and 54.9 inches, respectively. In addition to the measured data, an analysis of North American Regional Reanalysis (NARR) monthly latent heat data for Southern Florida from November 2002 to October 2003 was collected and compared to the observed potential evaporations rates. Based on the latent heat information the calculated evaporation from the C41-A-North water control catchment was 1132 mm/year [44.6 inches/year]. The NARR modeled values are 15% lower than the measured potential evapotranspiration values over a single year; however, the latent heat modeled in NARR is independent of the assumption that water evaporates at its potential rate. The distribution of evaporation, based on the information from NARR, is lower in the drier months and approximately equal to the observed potential evapotranspiration rates in the wetter months as reported in the C41-A-North water control catchment, Figure 7.

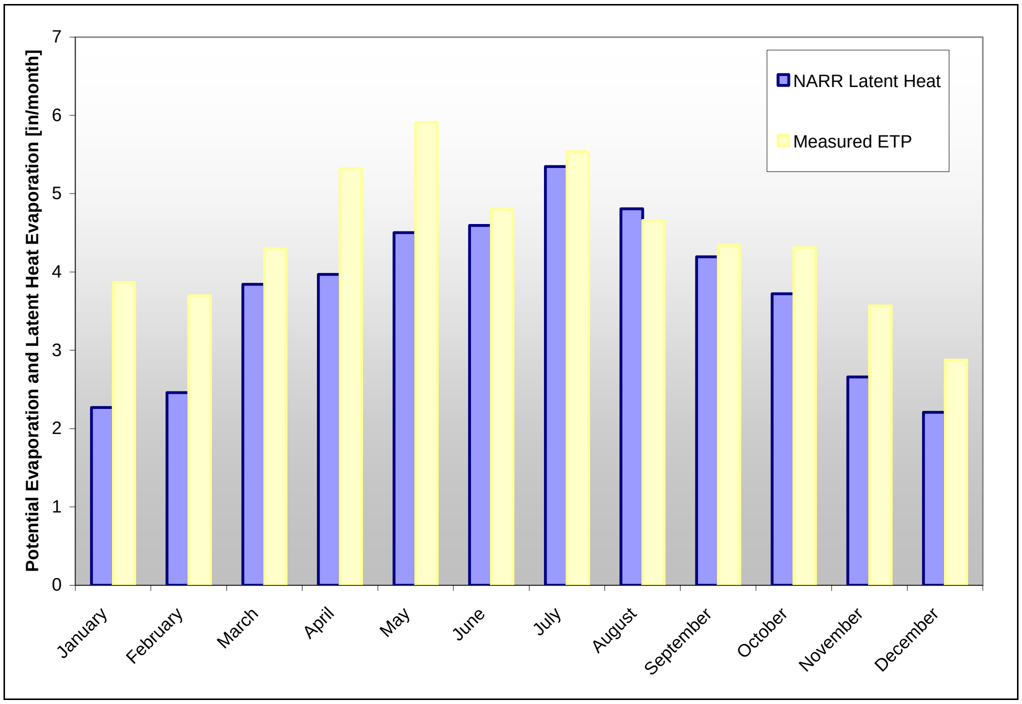


Figure 7 Comparison of reported potential evapotranspiration at S65CW and S65DW with NARR latent heat values

2.2 Precipitation Measurements

As mentioned in Section 2.1.1, rainfall is the driver of the water cycle in Southern Florida. Hydrologists are interested in how much rain falls over a given area, such as a basin or a watershed; they want to know the flux of rain over a given area for a given time period. Rainfall is a vertical flux in the water balance equation; however, it is historically measured as a rate at a point. As the terminology suggests, point rain gages are measurements of rainfall at a particular point in space, with rainfall measurements at different instances in time. However, rainfall has spatial and temporal variation that cannot be captured exclusively by a single point rainfall measurement. Different mathematical techniques have been developed to estimate the areal precipitation rate over a given area.

2.2.1 Point Rainfall Measurements

Historically there are three common techniques used to estimate areal precipitation rates from point rain gage data: arithmetic mean, Thiessen polygon, and isohyetal methods (Bedient and Huber, 2002).

The simplest method to estimate the areal precipitation area of an area from point measurements is the arithmetic mean technique, where the precipitation observed at each gage station within the watershed is assumed to represent the overall areal precipitation rate. Thus all rain amounts observed in the watershed are added together and divided by the total number of gages to get the average watershed areal precipitation rate.

$$\overline{R} = \frac{1}{n}\sum_{i=1}^{n} r_i \qquad \textbf{Equation 1}$$

where $\overline{R}$ is the watershed areal precipitation rate, n is the total number of gages within the watershed, i is the gage of interest and r_i is the rainfall rate recorded at each gage, i, in the watershed.

The Thiessen polygon method was developed in 1911 by Thiessen (Dingman, 2001) and is based on the assumption that any point in the watershed can be represented by the closest rainfall gage (Maidment, 1993). In order to construct Thiessen polygons straight lines are drawn between gages locations to form a network of triangles. Perpendicular bisectors are then drawn on each line and extended until they intersect other bisecting lines to create irregular polygons, Figure 8. Thiessen polygons are an excellent method to graphically determine the weights of each gage measurement on the estimation of areal precipitation rates. As presented by Dingman, the areal precipitation rate can be computed using Equation 2.

$$\overline{P} = \frac{1}{A}\sum_{g=1}^{G} a_g \cdot p_g \qquad \textbf{Equation 2}$$

where a_g is the area of each gage polygon, p_g is the measurement at gage g, and A is the total area of the watershed of interest.

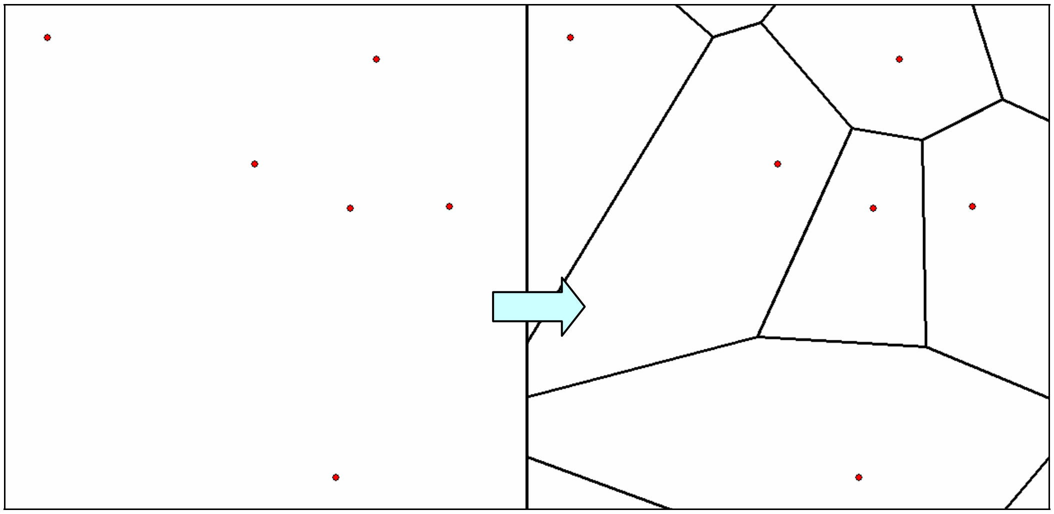


Figure 8 Thiessen Polygons for Areal Precipitation Estimation

Thirdly, the most complex method to estimate areal precipitation rates is the isohyetal method which involves interpolation of rainfall values between rain gages. An isohyetal is defined by the American Heritage Dictionary (2000) as "a line drawn on a map connecting points that receive equal amounts of rainfall." Bedient and Huber state that the isohyetal method is the most accurate of all three methods; however, that an extensive rain gage network is required to produce isohyets that are accurate between rain gages. However, Singh and Chowdhury (1986) found that the isohyetal method was no more accurate than any other areal estimation method using point gage data for two test sites in New Mexico. They looked at daily, monthly, and yearly precipitation estimates for the two regions and found that most methods fell within 10% of deviation from one another. With the use of computer software to interpolate between rain gage stations it is becoming increasingly more common to use interpolation techniques to estimate rainfall between rain gages. Historically isohyets were constructed manually between rain gage stations based on the hydrologist's judgment. In certain cases this technique is appropriate, particularly if other factors many influence precipitation rates. To calculate the areal precipitation rate for watershed, $\overline{P}$, it is assumed that all points that fall between isohyets have the same precipitation value, it is generally assumed that the precipitation between two isohyets is the average between the two isohyets, as expressed in Equation 3. (Dingman, 2002)

$$\overline{p_i} = 0.5 \cdot (p_{i-} + p_{i+})$$ **Equation 3**

Summing each subregion of precipitation and weighting the precipitation by the area that each isohyets set covers the following expression for the areal precipitation rate is found.

$$\overline{P} = \frac{1}{A}\sum_{i=1}^{I} a_i \cdot \overline{p_i}$$ **Equation 4**

Where a_i is the area between two isohyets and $\overline{p_i}$ is the estimate of precipitation for the isohyets.

2.2.2 NEXRAD Rainfall Measurements

Radar can be used to improve the estimates of rainfall variation, both spatially and temporally, compared to simple rain gage estimates. NEXRAD (next generation radar) was developed by the National Severe Storms Laboratory (NSSL) in conjunction with the National Weather Service (NWS), the Federal Aviation Administration (FAA) and the Air Force. (Bedient, 2002) Approximately 120 WSR-88D radars have been installed in the US and overseas. The acronym WSR stands for “weather surveillance radar” and 88 refers the year the devices was prototyped, 1988, and D refers to Doppler. Although the spatial density of the NEXRAD radars is much less than the NWS weather stations, the coverage of the contiguous US is much greater, due to the radar’s ability to detect rainfall between rain gages (Maidment, 1993). The NWS has approximately 278 primary weather stations which are staffed 24-hours a day by paid technical staff, compared to the 120 NEXRAD stations that cover the US (Dingman, 2002).

The spatial resolution of NEXRAD data can vary from approximately 4 km by 4 km grids to 1 km by 1 km spatial grids and can have a temporal resolution as small as 5 minutes (Maidment, 1993). Unlike rain gage measurements, NEXRAD radar measurements are not a direct measurement of rainfall, rather NEXRAD is a measurement of radar reflectivity. The basic principle that governs NEXRAD is the Doppler Effect. A NEXRAD radar emits a bust of energy, or signal, and the energy is sent out in all direction from the radar. If the energy signal strikes an object, such as a rain drop, bug, dust particle etc., the signal is scattered in all directions. A small portion of the signal is scattered back in the direction of the radar (NWS, 2005). The reflected signal is received by the radar and then interpreted using reflection versus rainfall relationships, called Z-R relationships (Maidment, 1993). The relationship between measured reflectivity and rainfall rates is generally expressed as a power function of the form:

$$R = aZ^b$$ **Equation 5**

where a and b are estimating parameters. The most commonly used power law used by the NWS is designed for convective precipitation events. This Z-R power law is:

$$Z = 300R^{1.4}$$ **Equation 6**

However, there are instances when the convective power law equation is not sufficient to describe precipitation events due to tropical storms or hurricanes, thus a second Z-R power law was developed to describe tropical precipitation events. The tropical power law equation will generally increase the amount of precipitation estimated by the radar by a factor of two (NWS, 2002).

$$Z = 250R^{1.2}$$ **Equation 7**

Several equations have been proposed by various researchers; however, calibration between NEXRAD measurements and rain gage stations is generally required to overcome the inherent errors in the Z-R relationships. (Bedient, 2002) The NWS produces adjusted radar precipitation results for distribution to the public. Private companies also distribute adjusted rainfall data with “value added” components to private consumers.

There are three levels of data formats and four stages of rainfall products produced by the NWS (NWS, 2002). Level II data is the first level of data, which is the base digital data from a single radar site. The information included in Level II includes base reflectivity, Doppler wind velocities, and spectrium width (Bedient and Huber, 2002). The second level of data is Level III data, commonly called Radar Product Generator (RPG). It is from this point that Stage rainfall data is derived. Stage I data is the least manipulated data of all four products. Stage I data is commonly called hourly digital precipitation (HDP) data. The HDP data set is created by the NWS by using the reflection-rainfall power law appropriate for the particular region and precipitation type. Computer programs are used to eliminate outliers and ground reflections in order to produce the Stage I rainfall precipitation estimates. The results of the Stage I analysis are then projected in the Hydrologic Rainfall Analysis Project (HRAP) grid which is used in the numerical weather prediction models run by the NWS. Stage I products are radar-only estimates of rainfall, there is no data correction applied to the data except computer applied algorithms for quality assurance. There can be significant overestimation of rainfall, up to a factor of two, or a significant underestimation of precipitation at the far reaches of the NEXRAD radar, well over a factor of ten. (NWS, 2002)

Stage II NWS products are rainfall estimations from a single radar station which have been adjusted using three different algorithms: mean field bias adjustment, gauge-only adjustment, and radar-gauge analysis. For more information on the particular methods used to adjust the NEXRAD radar rainfall grid please refer to the website maintained by the NWS to describe Stage III data. Once adjustments have been made to each radar station, the results are mosaicked together in order to produce the Stage III rainfall products (NWS, 2002). The development of the Stage III is much more labor intensive than both the Stage I and Stage II products since the data is quality controlled by NWS personnel. If changes are made to the input data or additional information is added to the analysis the Stage II product is reanalyzed and mosaicked across a River Forecast Center (RFC). (Geo et al., 2004) Stage III rainfall products are the most commonly used NWS product in the hydrologic community. (Xie et al, 2004) In the past, NEXRAD data generally underestimated the accumulated amount of areal precipitation over a watershed compared to the measured precipitation methods. This effect was based on the adjustment algorithms used by the NWS developed by Smith and Krajewski which had a tendency to significantly undercorrect the bias adjustment field. The old adjustment factor was replaced in the spring and summer of 1997. This adjustment has reduced the underestimation problem previously encountered. (NWS, 2002)

2.2.3 Rain Area Rainfall Measurements

There are 14 rainfall rain areas that cover the SFWMD. The rain areas were created to facilitate the daily operations of the Operations and Maintenance Department (OMD). The average area of the OMD fourteen rainfall basins is assumed, for operational purposes, small enough for rainfall characteristics to be statistically homogeneous. For a given duration, and a given year, the weighted average rainfall sum in a given area, based on the available data, is the best representative data for regional frequency analysis. Although this assumption may prove true for larger time scales; months and days; this assumption of heterogeneity of rainfall over a daily or sub-daily temporal time step may not prove accurate.

The method to evaluate the gage network data to estimate rainfall rates in the rain area is based on the Thiessen polygons method for computing a weighted average. In this method, a network of Thiessen polygons is configured based on the available data network. If the data network changes with time due to irregularities such as: gage malfunction, data screening, gages being added and/or dropped from the network, then a reconfiguration for a Thiessen Network is required for each configuration of the data network. Given that there are 14 rainfall rain areas in the SFWMD, the number of these temporal data irregularities is so high that evaluating an actual Thiessen Network for each case is computationally intensive. (Ali and Abtew, 1999)

2.3 Evaporation and Evapotranspiration Measurements

Unlike rainfall which can be measured by rain gages, evapotranspiration cannot easily be measured, due the large number of factors which influence the rate of evapotranspiration over an area. In many instances the estimation of evaporation or evapotranspiration from a water balance or energy balance method are fairly crude, since most water balance methods calculate evaporation/evapotranspiration, E, as the result of all the other inputs and outputs to the water balance, Equation 8, where P is net precipitation, V_R is the net volume of liquid entering or leaving the control volume, V_S is the change in liquid storage within the control volume, V_L is the volume of water leaving the control volume which cannot be measured and is thus an error term, and finally A is the surface area of the control volume. The estimation of evaporation from this method could apply to an abstract volume, such as a watershed, or an evaporation pan. Regardless of the control volume of interest, the estimation of evapotranspiration contains an accumulation of errors from all the other measured variables.

$$E = P - (V_R + V_S + V_L) / A \qquad \textbf{Equation 8}$$

2.3.1 Evaporation and Evapotranspiration

Evaporation is defined as the movement of water from the liquid phase to the gas phase in the atmosphere from open water, bare soil, or vegetation with soil underneath. (Maidment, 1993) The movement of water from the liquid to the gas phase is governed by diffusive processes that are modeled using Fick's Law. (Dingman, 2002) The two main factors that impact the rate of evaporation from an open water system are the input energy required to vaporize the liquid water and a mechanism to transport the vaporized water away from the free water surface. (Chow et al., 1988) Evaporation is defined only for the direct movement of liquid water from the soil or plants to the atmosphere and does not cover the transpiration of water through plants and water which is diffused to the atmosphere. To capture both mechanisms of phase transfer and water movement the term evapotranspiration is commonly used. The rate of evapotranspiration is impacted by the input energy into the system, a mechanism to transport the water vapor away from the free water surface, and the availability of water or moisture at the evaporative surface.

For all intents and purposes, the measurement of evapotranspiration is difficult and costly, thus an alternative measurement is commonly used in hydrology, potential evapotranspiration. Potential evapotranspiration is defined as the quantity of water evaporated from an idealized, extensive free water surface under existing atmospheric conditions per unit area, per unit time. (Maidment, 1993) Potential evapotranspiration is not limited by the availability of moisture to the vegetation. Thus as soil dries out the actual rate of evapotranspiration from a vegetated surface is less than the potential evapotranspiration. Another commonly used term is "reference crop evaporation", which is defined as the rate of evaporation from an idealized grass crop with a fixed height, albedo, and surface resistance to evaporation.

2.3.2 Pan Evaporation

The most common method to estimate potential evapotranspiration is the pan evaporation method. A pan is filled with water to provide a free surface for water to evaporate from. The evaporation rate from the pan is calculated by the change in volume in the pan over a selected time period, commonly one day.

$$E_{pan} = W - [V_2 - V_1] / \mathbf{A} \qquad \textbf{Equation 9}$$

Where W is the recorded precipitation during a selected time interval, V_1 and V_2 is the volume storage in the pan at time t_1 and t_2 and A is the area of the pan. The difference between the loss of water due to evaporation and the addition of water due to precipitation is the measured pan evaporation rate. It has been found that the rate of evaporation from a pan is generally higher than the evaporation rate from surrounding free water surfaces. This is most likely due to the turbulence of water within larger water bodies, which is not found in the evaporation pan which transfers energy, solar radiation, from the water surface to other portions of the water body, thus decreasing the overall rate of evaporation. In order to compensate for the over estimation of evaporation and evapotranspiration by the pan method empirical pan coefficients are used to estimate the accurate evaporation and evapotranspiration rate from the surrounding landscape. (Maidment, 1992)

$$E_{actual} = kE_{pan} \qquad \textbf{Equation 10}$$

Where E_{pan} is the measured evaporation from the pan, E_{actual} is the estimated actual evaporation and k is the pan coefficient. There is a wide range of pan coefficients that can be applied to a given landscape; however, there is limited fluctuation of the evaporation rates over a given year, less than a ten percent variation in most climates. (Maidment, 1993) Evaporation data from year to year does not typically change;

therefore, a few years of data can prove very insightful for the estimation of evaporation and evapotranspiration rates in the future. (Dingman, 2002) However, these two conclusions were made on a monthly and yearly basis, thus the assumption of limited variability between time intervals may not prove true from smaller time steps on daily or sub-daily time steps.

2.3.3 Measured Evapotranspiration in the South Florida Water Management District

Abtew et al 2003 looked at method to estimate the daily evapotranspiration rate within the SFWMD using six different methods which ranged in complexity from the very simple, a radiation model, to the very complex, a Penman-Monteith model. Since 73 percent of the variation in daily evapotranspiration is associated with changes in solar radiation, the impact of other factors that effect evapotranspiration: humidity and wind speed, are minimal in the SFWMD. Comparing the results of the six different estimation methods all the methods produced similar results. Abtew et al state that the three simple methods tested, Radiation method (Equation 11), Modified Turc (Equation 12), and Radiation/Tmax (Equation 13) methods produced similar results to the Penman-Monteith equation with far fewer variables.

$$ETp = K_1 \frac{Rs}{\lambda} \qquad \textbf{Equation 11}$$

Where ETp is the daily potential evapotranspiration [mm/d], Rs is the solar radiation [MJ/m^2/d], l is the latent heat of vaporization [MJ/kg] and K_1 is a fitting coefficient [0.53].

$$ETp = K_2 \frac{(23.89Rs + 50)T_{\max}}{T_{\max} + 15} \qquad \textbf{Equation 12}$$

Where T_{max} is the maximum daily temperature is degrees Celcius and K_2 is a fitting coefficient [0.012].

$$ETp = \frac{1}{K_3} \frac{Rs \cdot T_{\max}}{\lambda} \qquad \textbf{Equation 13}$$

Where K3 is a fitting coefficient [56^{o}C].

There are 25 weather stations within the SFWMD that measure solar radiation, temperature, and wind speed. Thus, it is possible to estimate the potential evapotranspiration rate for the SFWMD using real-time measurements for solar radiation, temperature, and wind speed.

2.4 Water Managers

Making water management decisions on a daily basis is the job of the four water managers employed by the SFWMD. Water management decisions are based on regulations, codes and water management goals set by the SFWMD and the state of Florida. Using the their knowledge of the state of the hydrologic system and observed water levels and flows in the system, the water managers develop a water management strategy that is implemented by the OMD operators and field personnel. Water managers in the South Florida Water Management District are tasked with the daily development of water management strategies for the SFWMD based on the current state of the water system, regulatory requirements, and forecasted weather patterns. The state of the SFWMD water system, canals and lakes operated by the SFWMD, is based on the water levels observed throughout the SFWMD. (Amadori, 2004) Based on the observed data, over 3000 parameters gathered by the SCADA system used by the SFWMD, and the forecasted meteorological data used by the SFWMD a water manager develops a water management plan to meet the objective of the district: flood control, water supply, and environmental protection

$$StateoftheSystem + Forecast + Objectives \rightarrow Strategy \qquad \textbf{Equation 14}$$

Each water manager is responsible for a different geographic location of the SFWMD, while all four managers are tasked with a different region the water management strategy developed by each water manager is a cohesive plan. All water management strategies developed by the SFWMD water managers are based on regulations and water management codes. Once a water management strategy is developed by the water managers the strategy is communicated to Operators, who are responsible for implementing the water management strategies and monitoring the state of the system. In certain cases a water manager may be called upon to explain the water management strategy that they developed to SFWMD board members, senior leadership, or customers with either an informative or defensive posture. In either case, the water managers need as much information as possible about an event in question. Historical information is needed to provide current events with an historical perspective. (Amadori, 2004)

2.5 Test Area

The SFWMD covers a region of approximately 17,000 square miles, which covers over 25% of the state of Florida. The entire SFWMD is too large to develop a prototype for an operational decision support system; therefore, the CRWR proposed a smaller region of focus in order to develop the Operational Decision Support System (ODSS). In order to develop an understanding of the horizontal and vertical components of the water balance that are applicable to the entire SFWMD region a region termed the Three Lakes Region was proposed, Figure 2. The region selected includes Lakes Okeechobee, Istokpoga, and Kissimmee, and was selected based on the inclusion of these large lakes, minimal to no tidal influences, watersheds of significant size, and two types of hydraulic flow system: multiple flow paths and single flow paths. The selected region has been termed the Three Lakes Area or Prototype Test Area, Figure 2. The general flow of water in the Three Lakes Region is from North to South, with most of the water leaving Lake Okeechobee flowing to the South and Southwest.

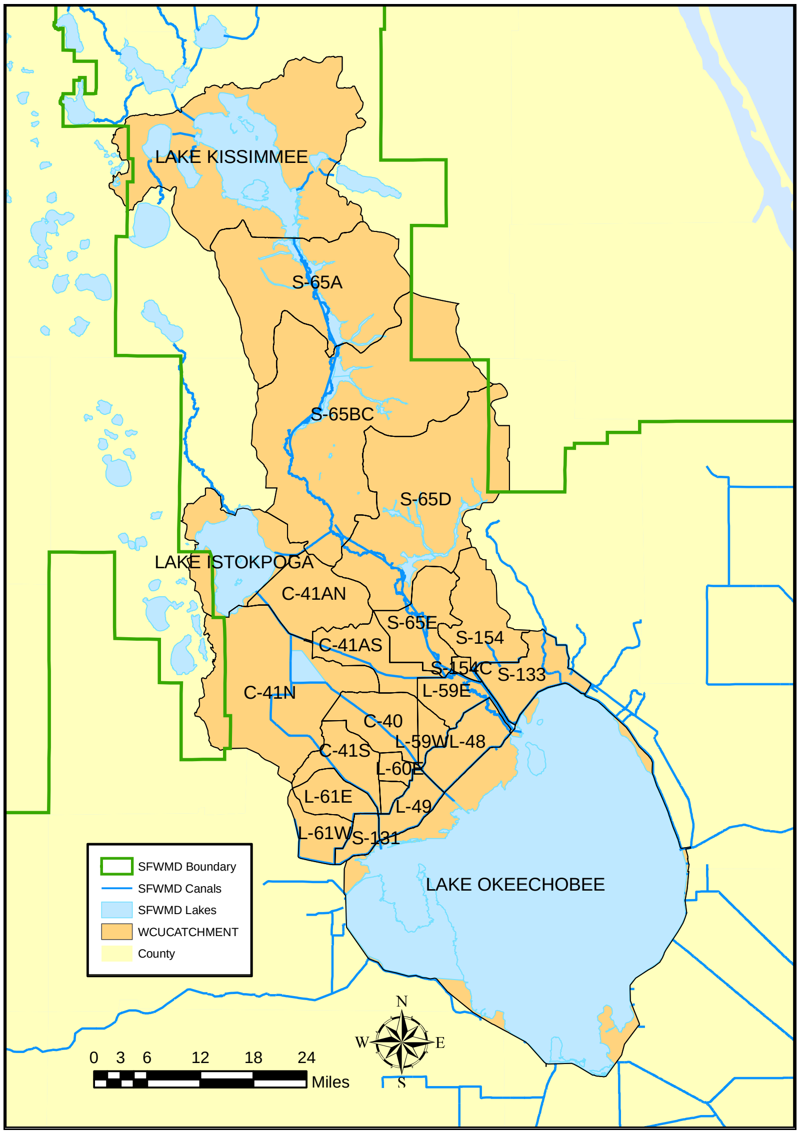


Figure 2 Three Lakes Test Area for development of Operations Decision Support System

Upstream from Lake Okeechobee lies the Upper Kissimmee basin, which is dotted with hundreds of lakes, ranging in size from small sinkholes and ponds to large lakes, such as Lakes Kissimmee and Istokpoga. The surface water drainage pattern begins with the Kissimmee Chain of Lakes, a series of interconnected lakes in central Florida beginning near Orlando. Most of these lakes are shallow, with mean depths varying from 6 to 13 feet. Surface water generally flows southward to Lake Kissimmee, then onward to Lake Okeechobee via the Kissimmee River. (Florida DEP, 2003)

However, even this test region is a significant size, encompassing 1,448,936 acres [2264 square miles]. To develop a general understanding of water balances and the time dependent components of water balancing a single watershed, C41-A-North, was selected based on the multiple inlets or outlets to the water control catchment. Thus if a water balance method could be developed to predict the water demands and storage within the basin, then the water balance method should theoretically apply to all types of basins.

2.5.1 C41-A-North Water Control Catchment

The C41-A-North water control catchment is located just downstream of Lake Istokpoga and contains the canal C41-A, for which it is named. The catchment is approximately 34280 acres [13872 hectares] in size. Flow through the C41-A-North water control catchment is control by three structures, S68, S82, and S83. The S68 structure controls the flow of water into the water control catchment and the remaining two structures S82 and S83 control the flow of water out of the water control catchment and into water control catchments C41-North and C41-A-South respectively, Figure 9. Approximately 5% of the water control catchment is covered by the C41-A canal.

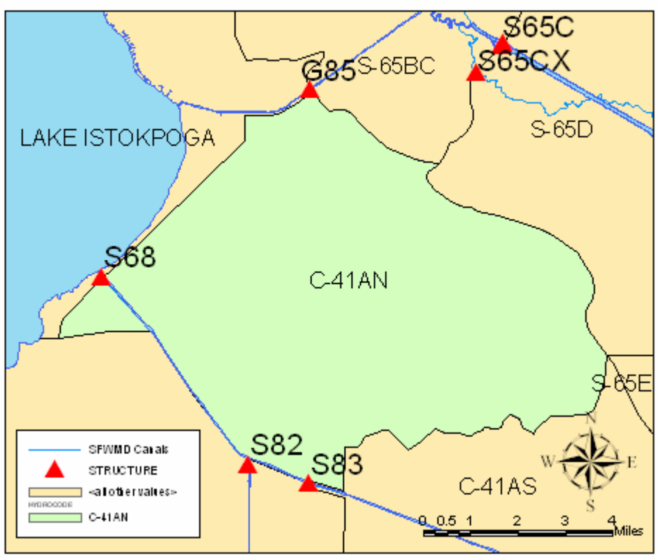


Figure 9 C41-A North Water Control Catchment in Three Lakes Area

The S68 structure is one of two structures maintained by the SFWMD that control the level of Lake Istokpoga. The S68 structure is used in high stage periods to prevent Lake

Istokpoga from over topping the structure and causing damage downstream. In low flow periods the structure is used to maintain the downstream stage and irrigation demands of water users downstream from Lake Istokpoga. Structure S82 is operated to restrict canal discharge from C41-A-North into C41 North when the C41-North canal is needed to contain local runoff. Structure S83 is designed to discharge the entire flood flow demand of the C41-A-North canal. During low flow periods it will allow up to 300 cfs of water to be released for agricultural use. Both S82 and S83 structures are operated jointly to maintain an optimal headwater elevation in canal C41-A-North between 31.8 and 32.2 feet above sea level.

2.5.2 Lake Okeechobee Catchment

Lake Okeechobee is the second largest fresh water body after Lake Michigan contained entirely within the continental United States. However, unlike the large Lake Okeechobee is very, with an average water depth of 9 feet. Lake Okeechobee covers an area of approximately 730 square miles (SFWMD, 2005b). Lake Okeechobee is commonly referred to as the liquid heart of Southern Florida. The name Okeechobee comes from the Seminole word meaning “big water”.

The water level in the lake has varied between 9.2 feet and 18 feet above mean sea level during the last two decades. It has an average depth of 8.6 feet and a maximum storage capacity of 1.05 trillion gallons. Releases of water from Lake Okeechobee into downstream canals recharge the surficial aquifer in most of Palm Beach County and the Biscayne Aquifer farther south, indirectly supplying water to the five million residents of southeastern Florida. In addition, the lake serves as a backup water supply for communities along the Caloosahatchee River, and supplies irrigation water for agriculture. The lake also provides water storage to meet the District flood control mandate.

Major inflows into the lake include rainfall (47 percent), the Kissimmee River (25 percent), and numerous smaller inflows (all 5 percent or less) from the Harney Pond and

Indian Prairie basins, Fisheating Creek, and Taylor Creek/Nubbin Slough. Major outflows include evapotranspiration (64 percent), releases to the Caloosahatchee River to the west (12 percent), releases to the St. Lucie Canal to the east (4 percent), and 4 major agricultural canals (West Palm Beach, Hillsboro, New River, and Miami) that drain to the southeast (<20 percent) (SFWMD, 1997). The 4 agricultural canals carry irrigation water to the Everglades Agricultural Areas (EAA) and release excess water to the Water Conservation Areas (WCA) when storage and discharge capacity is available. (Florida DEP , 2003)

2.6 Operations Decision Support System

As part of an overall SFWMD initiative to create an enterprise level geodatabase to maintain the integrity of spatial data maintained by the SFWMD, a secondary level project was created: the Operations Decisions Support System (ODSS). The Arc Hydro Enterprise Database (AHED) is a customization of the Arc Hydro data model created by Dr. David Maidment at the Center for Research in Water Resources (CRWR) and PBS&J. The customization of the Arc Hydro data model for the SFWMD initiative is intended to reduce redundancy in the management of spatial information across the District. (PBS&J, 2004a) Four prototype projects, encompassing a wide variety of project types undertaken by the SFWMD, are associated with the development of the AHED project, these prototype projects are: Operations Decision Support System, Hydroperiod Analysis, Regional Simulation Model, and Flood Modeling. (PBS&J, 2004b) All four prototype projects require accurate spatial and temporal data to produce accurate and useful results in a timely manner to the AHED user. By creating a common geodatabase structure for all four projects to use and store common spatial information, while maintaining spatial and temporal data specific to each project in separate feature data sets, there is a reduction in the duplication of geographic data maintained and stored by the SFWMD, while ensuring spatial integrity between each project. (PBS&J, 2004b)

2.7 Arc Hydro Enterprise Database

The Arc Hydro Data Model is an extensible, flexible, and adaptable data model that can be customized for case-specific database design. Arc Hydro takes advantage of the next generation of spatial generation for spatial data in a Relationship Database Management Systems, the geodatabase model. Conceptually, a geodatabase is a combination of Geographic Information System (GIS) objects enhanced with the capabilities of a relational database to allow for relationships, topologies, and geometric networks. (CRWR, 2004) The Arc Hydro data model, Figure 10, is meant to be extensible and adaptable depending on the project. The base Arc Hydro data model is not meant to include all information that pertains to every project, but rather is a starting point from which hydrologic and hydraulic projects within GIS can be formulated. Each project can include additional data, within feature classes and relationships, or include hydrologic or hydraulic modeling through data interfaces. (Maidment, 2002)

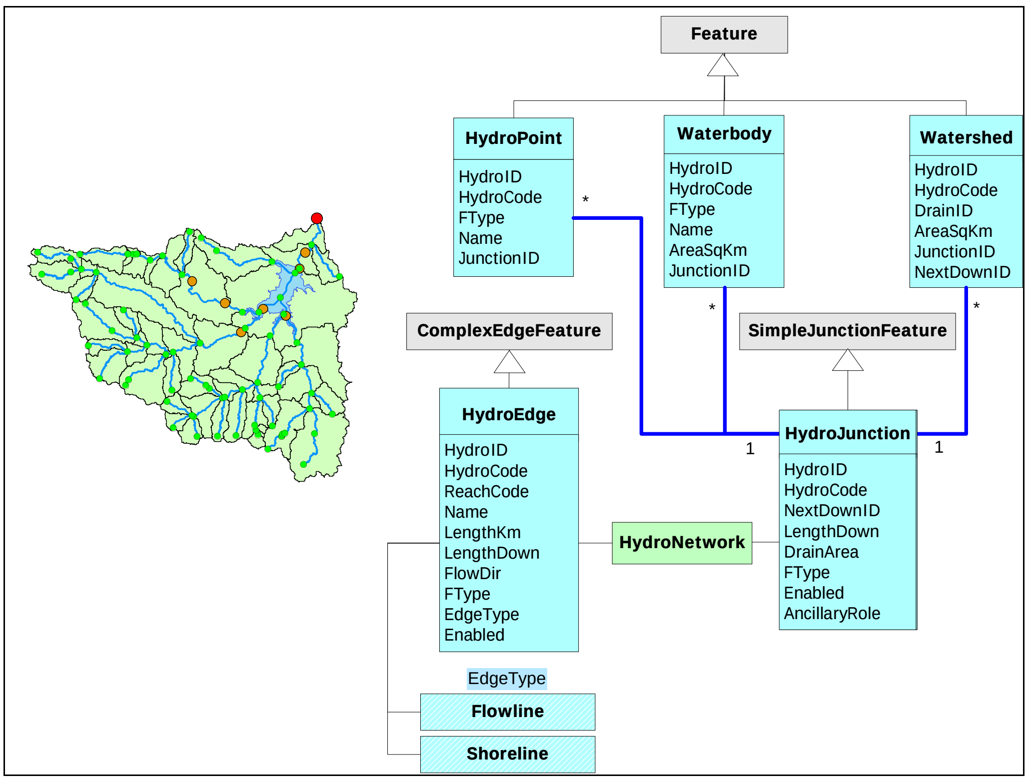


Figure 10 Arc Hydro Framework Data Model with base Feature Classes and Relationships

2.8 Model Development

In development of the ODSS, two unique definitions were the starting points in order to define the types of hydrologic properties the ODSS uses: water control units (WCU) and water control catchments (WCC). These two definitions are slightly different from the general definitions of a stream or a water body and a watershed, respectively.

2.8.1 Water Control Unit

The initial definition of a water control unit was provided to CRWW by the SFWMD which defined a water control unit as a portion of the hydrologic network whose water level can be controlled by structures at primary and secondary inflow/outflow points at its boundaries and is controlled as a single unit, Appendix B. These boundary points could either by defined by structures or no flow conditions; both boundary conditions exist in the Three Lakes test area. Conceptually one could think of a water control unit as either a single water body or multiple water bodies whose water surface would be level at all points in the water control unit if all structures were closed to prevent the movement of water from one water control unit to another. This definition of a water control unit implies that the water level at one point in a water control unit is dependent on the water level at every other point in the water control unit; conversely, the water level in one water control unit is independent of the water level in another water control unit. In hydrologic terms it is simple to think of a single water body, such as a canal or lake whose water level is dependent on the water level at every other point in the water body; however, as defined above, as water control unit is potentially comprised of multiple water bodies, such as a canal and several lakes.

2.8.2 Water Control Catchment

Once a water control unit is defined then the contributing drainage area to the water control unit is defined as the water control catchment (WCC) (PBS&J, 2004b). A water control unit can be considered the operationally significant portion of the water control unit network. A water control catchment is defined as the extent of land surface area that drains into a water control unit. It is assumed that the boundaries of each water control catchment are no-flow boundaries, that all the water that enters a water control catchment leaves due to evapotranspiration or flow though the structures that bound the associated water control unit.

2.8.3 Operationally Significant Water Bodies

The terminology "operationally significant" is used within this thesis to define water bodies and land areas that are of interest or importance to decisions made at an operational management level. There are thousands of water bodies in the South Florida region, not all of the water bodies are of operational significance to a water manager's decision making; thus, to minimize the potentially thousands of water bodies that could fall under a water manager's decision only a small portion of the water within the SFWMD is considered a part of the operational water system. The definition of operationally significant water bodies is important with the use of the 1:24,000 resolution National Hydrography Dataset (NHD), sometimes referred to as 24K NHD. Prior to the existence of the 1:24,000 resolution data all of the data described by the NHD was in digital line graph format at a resolution of 1:100,000. At the finer resolution water bodies, such as lakes, ponds, rivers, and streams are represented by digital lines; however, with the production of 1:24,000 resolution data, the representation of water bodies is by lines and polygons. Thus, the amount of information contained with the 24K NHD is much larger; however, more information in this case does not necessarily mean more useful information, Figure 11.

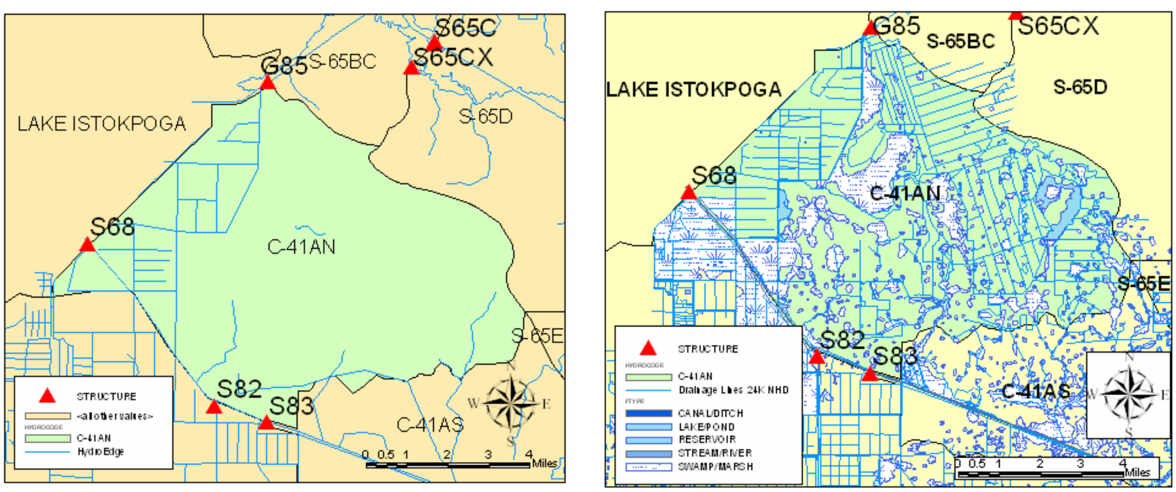


Figure 11 1:100,000 and 1:24,000 resolution NHD data for the C41-A-North water control catchment

As shown in Figure 11, the representation of water bodies at a high level of detail in the South Florida region does not mean that the data is useful to operational decisions. In fact, the water bodies shown on the right side of the Figure 11 include water bodies that vary in size from 6600 square feet to 165,000,000 square feet [3788 acres]. Water bodies on the order of 6600 square feet are generally not assumed to be of operational significance. As well, due the flat topography of southern Florida many water bodies are not directly connected to the operational surface water system. Therefore, to accurately reflect the water bodies that water managers deem to be of operation significance, the water bodies defined by the 24K NHD the water bodies were divided into two types: Type 1 includes water bodies that are of operational significance and Type 0 water bodies that are deemed not to be of operational significance SFWMD personnel determined which 24K water bodies were or were not part of the SFMWD managed water system. Water bodies that were part of the managed water system were given a Type 1 designation and water bodies not part of the SFWMD managed water system were given a Type 0 designation. This approach reduces the total number of water bodies required for analysis in the Three Lakes test region from 14209 to 39, yet still keeps the geographic description of the operational water system controlled by the SFWMD, Figure 12.

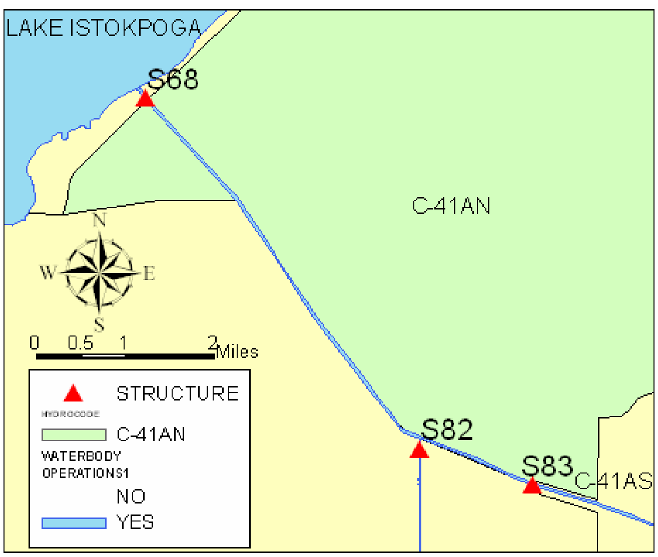


Figure 12 Polygon features describing the operationally significant water bodies of the C41-A-North catchment

2.8.4 Operational Decision Support System Data Model

Using the definition of a water control unit and a water control catchment (Sections 2.8.1and 2.8.2) a data model or conceptual model, of the operational decisions support system database is created. As with the Arc Hydro data model the ODSS data model describing a network of water control units within the landscape of the SFWMD. Thus, an ODSS data model must include a network to describe the water control units, Figure 13. Within the schematic network, two other features are represented by nodes: the water control catchments and the structures that define the beginning and at end of each water control unit. Each node type is defined as a separate node type; a Type 1 node represents a water control unit, a Type 2 node represents the structures that define the extent of a water control unit, and a Type 3 node represents the water control catchments that drain to each water control unit.

The relationships between the features in the data model are best described referring to a UML diagram of the data model, Figure 14. The central building block of the data model is the WCUNode feature class, which is a schematic representation of water control units, water control catchments, and control structures. To represent the water control unit network a second feature class, WCULink, is created. The WCULink is used to describe the physical link between the three types of WCUNodes, Figure 13. Each water control unit node is related to one water control catchment node, creating a schematic link between the water bodies described with the water control unit and the land surface described by the water control catchment. Multiple WCUNode features can be related to multiple structures defined in the general geospatial feature data set AH_ENHANCEDARCHYDRO. This relationship occurs because that multiple components of a single structure facility can be controlled independently or in certain instances several structures can define the end of a single water control unit. For example, along the Kissimmee River three structures can define the end of a water control unit; however, only one is of operational significance, in this case structure S65-C is the only structure of operational significance. Finally, based on the Arc Hydro data model each HydroJunction feature can be associated with multiple structures or one WCUNode.

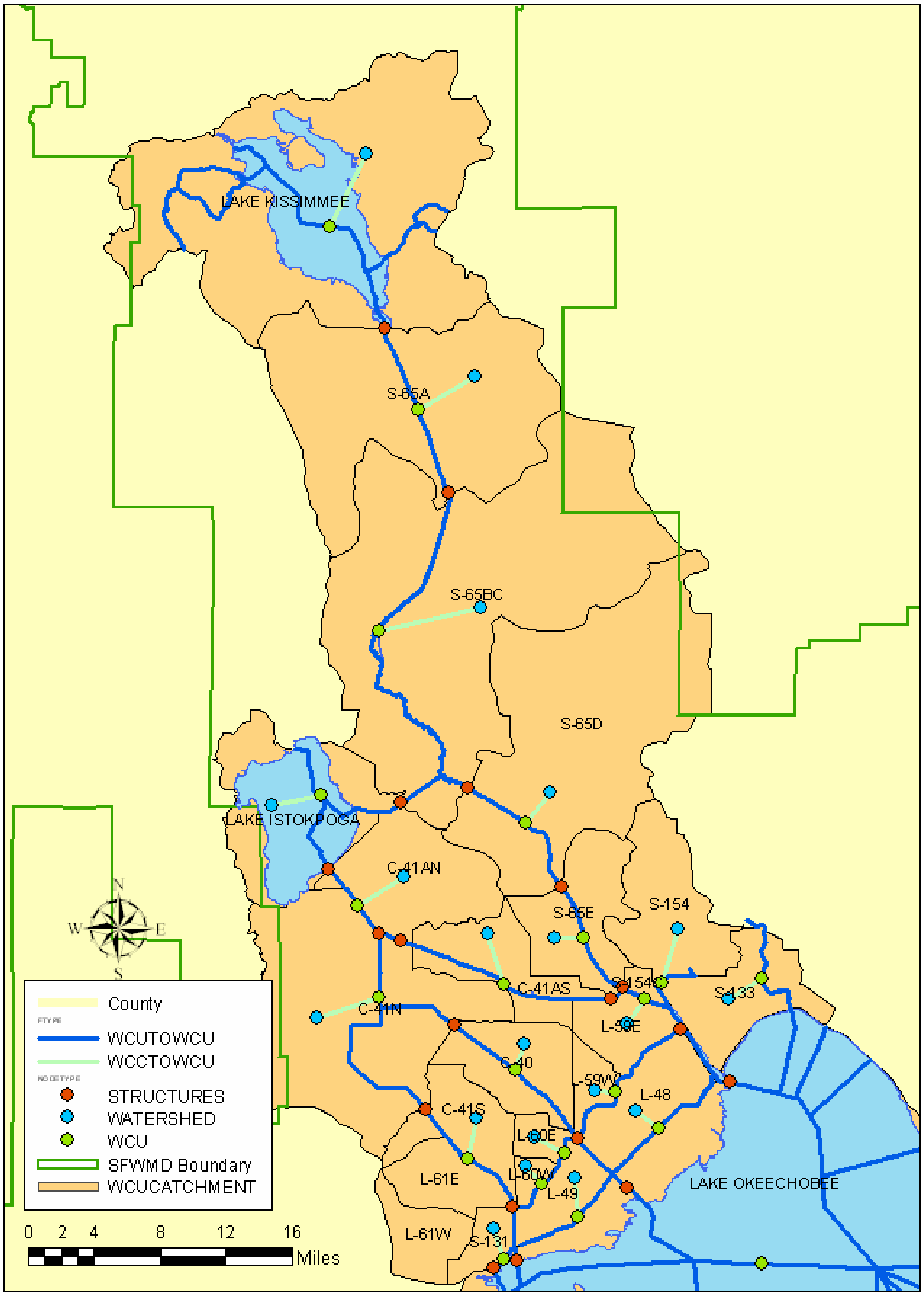


Figure 13 Schematic Network Representation of the Water Control Unit Network

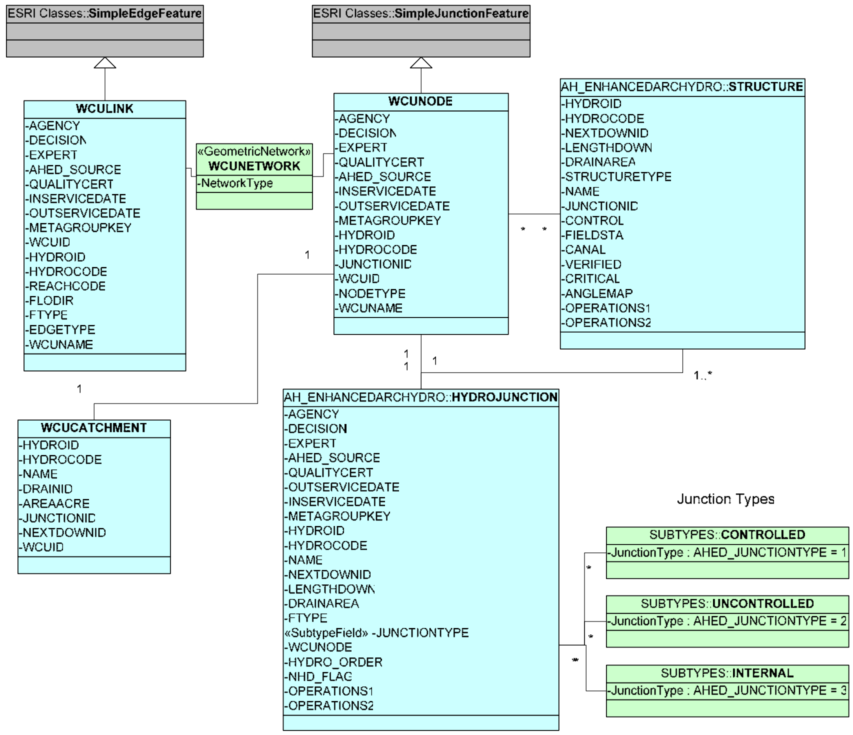


Figure 14 UML Diagram of Operational Decision Suppoart System Data Model

2.8.5 Operational Decision Support System Feature Data Set

The Operational Decision Support System is only one aspect of the overall Arc Hydro Enterprise Database developed by the SFWMD. The ODSS feature data set, AH_ODSS, set is one of four project-specific, feature data-sets contained in the AHED geodatabase, Figure 15. A general feature data set, AH_ENHANCEDARCHYDRO, contains spatial data that is generic and applicable for all projects taking place in the SFMWD, such as structures, monitoring points, and water bodies that are operationally significant to the SFWMD. However, the enhanced Arc Hydro data set does not contain information that is project-specific and is not determined to be of importance across the entire SFWMD.

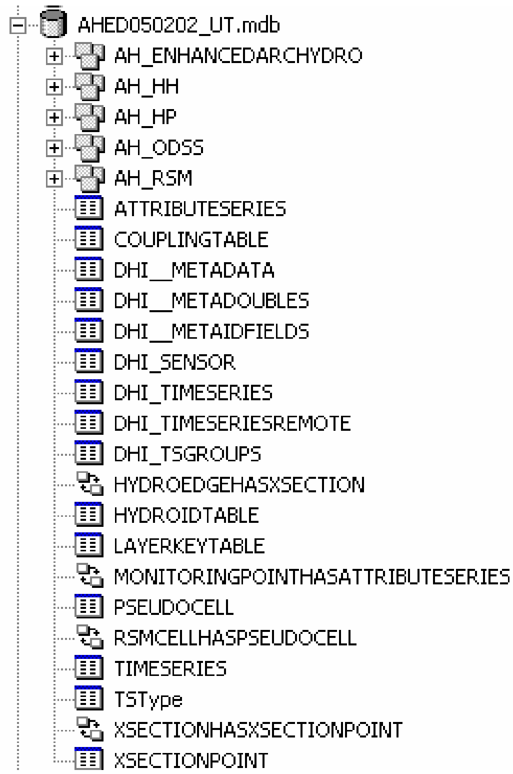


Figure 15 Arc Hydro Enterprise Database developed for SFWMD

Although the general feature data set, AH_ENHANCEDARCHYDRO, contains the majority of spatial data in the AHED, the water control unit and water control catchment hydrologic features are not described by the spatial features and relationships within this feature data set. Thus, an ODSS-specific feature data set is included in the AHED, which contains the geographic information described in the ODSS data model, Section 2.8.4, Figure 16. The three feature classes described in the data model, WCUNode, WCULink, and WCUCatchment are all found within the ODSS feature data set.

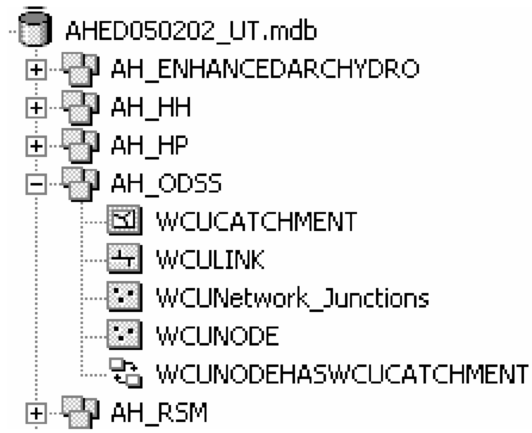


Figure 16 Operational Decision Support System Feature Data Set in AHED personal geodatabase

In the most recent version of the AHED personal geodatabase there are 60 schematic nodes and 24 catchments described in the feature data set, with multiple links describing the relationship between the nodes. The creation of the schematic network is documented in Appendix C.

3 Methodology

The methodology presented covers three main topics: the geospatial water balance over a water control unit and water control catchment, the definition of potential inputs into the water balance, and third, the methodology developed to display the results of the water balance within Arc GIS.

3.1 Hydrologic Fluxes and Flows

Construction of a water balance over a control volume concerns two different types of water movement, fluxes and flows. A water flux occurs at along a line or area, where as a flow occurs at a point in space. Within these two types of water movement there are two directions which water can flow, horizontally and vertically. As part of the current research of the Consortium of Universities for the Advancement of Hydrologic Science, Inc (CUASHI) several rinsights have been documented. Mainly, that there are four basic properties of water movement through a watershed that are important for hydrologic analysis. These properties are: the mass of water stored in the watershed, the residence time of water stored in the watershed, the fluxes between the different components of the watershed's hydrologic cycle, and the flowpaths between the components of the watershed's hydrologic cycle (Maidment et al, 2005). This thesis looks at two of these four properties, namely, estimating the amount of water mass stored in a watershed over a period of time, and secondly the fluxes between the different components of the watershed's hydrologic cycle.

In the case of the SFWMD, there are two distinct components of interest in the movement of water through the SFWMD. The operational water bodies are heavily monitored by stage measurements and weather monitoring stations, generally located within close proximity to the operation water system. The second component of the system, the landscape, is generally less understood and monitored. The movement of water between the landscape and the operational water bodies it not uni-directional, but rather is bi-directional, depending on the hydrologic state of the landscape. The movement of water between the landscape and the water bodies is controlled by structures, levees, and other apparatuses that are not managed by the SFWMD. Therefore, the movement of water between the landscape and the water bodies is not measured. If the landscape, represented by water control catchments, is extremely wet and cannot contain any more water without damage to the landscape, the water is drained from the landscape to the operationally significant water bodies, represented by water control units. Conversely, if the landscape is dry or vegetation needs additional water to meet demands, water is drained from the water control units to the water control catchments, Figure 17.

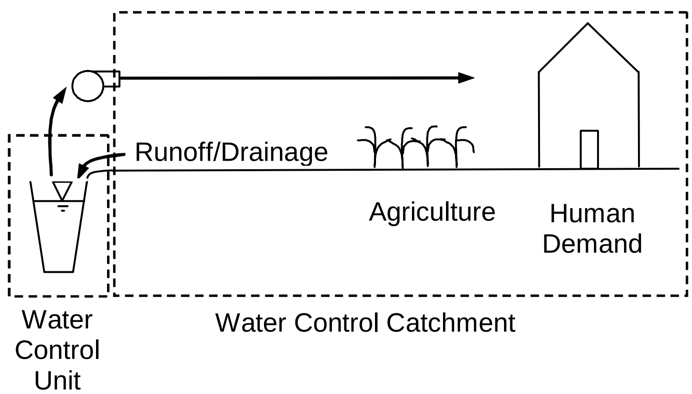


Figure 17 Diagram of potential water movement between Water Control Unit and Water Control Catchment

Since the movement of water from the water control catchments to the water control units is not necessarily controlled by the SFWMD and the actual amount of water being input or withdrawn from the water control units is difficult to know, the only method to estimate water movement between the two components is to assume that the movement of water between the two components is the unknown component of a water balance over the water control units. In an effort to estimate the movement of water between the two components a geospatial water balance approach was proposed by water managers at the SFWMD. The purpose of the geospatial water balance is to estimate the amount of water that will enter or leave the water control unit over a short time period. However, in order to represent the movement of water between control volumes and the mass of water stored within a control volume within a GIS structure, a GIS data model must be constructed. To estimate the amount of water mass stored within a control volume, the inputs and outputs of the control volume are required, as well as the type of movement of mass, whether it is a flow, a line flux or an area flux. All three movements of mass interact with the control volume; however, the mathematical representation of a line flux versus an area flux is different, thus they must be computed differently.

3.2 Simple Water Balancing

The concept of water balancing is a fundamental to hydrology and water resources planning and management. However, performing time-varying water balance calculations within the current Arc Hydro framework, or the GIS software platform in general can be a tedious and labor intensive process. GIS does a poor job of handling spatial and temporal varying components, such as rainfall (Al-Sabhan, 2003). Water movement within a control volume is not only affected by fluxes, such as rainfall, infiltration, and evaporation, but also horizontal flows through the landscape. The ability to link the vertical and horizontal water balances within an ArcGIS framework is a necessary step in the development of the SFWMD ODSS. A water manager at the SFWMD thinks of the movement of water in two distinct components, the movement of water in water control units (WCU) and the movement of water in water control catchments (WCC).

Water managers have an excellent understanding of the movement of water through operationally significant water bodies, such as those defined water control units; however, the movement of water on and through the water control catchments is less well understood. Thus, the purpose of the geospatial water balance is two-fold: 1) develop a link between the water control units and the water control catchments using water budgets, and 2) predict the state of the water control units to give water managers indices of amount of water contained within each water control unit and water control catchment.

The conservation equation is an appropriate model to determine the movement of mass through a control volume, Figure 18; where the change in storage within a control volume, dS/dt, is equal to the difference between the input and the output during the same time interval. Visualizing an abstract control volume and the movement of water through the control volume.

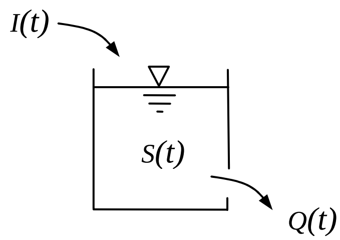


Figure 18 Continuity of water stored in a hydrologic system (based on Chow et al., 1988)

$$\frac{dS}{dt} = I(t) - Q(t) \qquad \textbf{Equation 15}$$

In discrete time intervals the change in storage can be expressed as the difference between the inputs and outputs of mass over the same time step:

$$\Delta S_{t=1} = I_{t=1} - Q_{t=1} \qquad \textbf{Equation 16}$$

Expanding the conservation equation into measurements that are specific to hydrology and hydraulics the conservation equations looks like:

$$P + G_{in} - (Q + ET + G_{out}) = \Delta S \qquad \textbf{Equation 17}$$

Where P is precipitation, in this report precipitation is assumed there is no solid precipitation, such as hail and snow, unless otherwise indicated, G_{in} is groundwater inflow relative to the control volume, Q is stream inflow, ET is evapotranspiration out of the control volume, G_{out} is groundwater outflow relative to the control volume, and ΔS is the change in storage within the control volume.

3.2.1 Water Balance over a Water Control Unit

Looking first at a single water control unit in the ODSS as a control volume the change in storage over a small time period is determined the following inflows and outflows: inflows from water flowing through monitored structures, outflows from water flowing through monitored structures, inflows from rainfall directly on the water bodies, outflows from evaporation directly from the water bodies, inflows from water between the landscape and the water bodies. The transfer of water term, Q_{TRANS}, contains the residual error term for the water balance; it is the only calculated term in the analysis. All other terms in the water balance equations are directly estimated from measurements recorded in the field.

$$\Delta S_{WCU} = Q_{in} - Q_{out} + P_{WCU} - ET_{WCYU} + Q_{TRANS} \qquad \textbf{Equation 18}$$

However, the above equation does not take into account that rainfall measurements and evaporation measurements provide estimates of fluxes, while the remaining components of the equation are flows. To correctly convert all of the data into the same units the following equation must be used with the surface area of the water body used in the calculation.

$$\Delta S_{WCU} = Q_{in} - Q_{out} + Q_{TRANS} + (q_{Rain} - q_{ET})A \qquad \textbf{Equation 19}$$

where A is the estimated surface area of the water body of interest. A schematic representation of the fluxes and flows that enter and exit a water control unit are shown in, Figure 19.

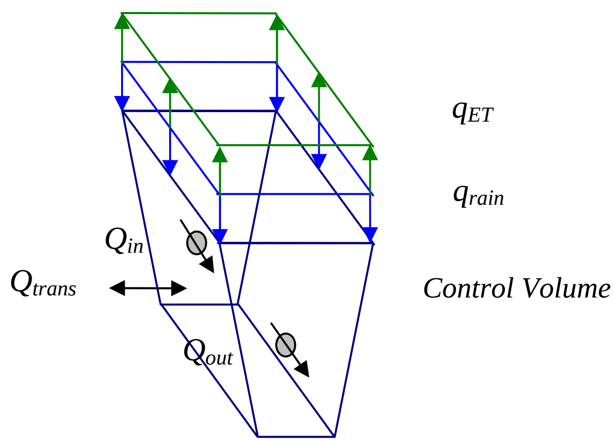


Figure 19 Schematic representation of fluxes and flows into and out of a water control unit

Estimates of structure flow were retrieved from the SFWMD's database management system DBHydro. DBHydro is the corporate environmental database that stores a vast amount of hydrologic, meteorologic, hydrogeologic, and water quality information. The database is accessible to the public and contains historic and near-time environmental data collected with the SFWMD, instead not all time series information is available (SFWMD, 2005c). The flow estimates reported in the DBHydro database are based on calculations specific to each structure. Flow is not measured directly at each structure; but the upstream and downstream stage levels are recorded. Based on the recorded stage levels the flow is estimated using flow equations specific to each structure. Since flow is not a direct measurement, there is the potential for measurement error with each measurement.

Rainfall directly onto a water body is ignored in many hydrologic calculations, and in many cases within the Three Lakes region the total area of the water control units is much less than the area of the water control catchment, i.e. covering less than 1% of the total catchment area. For example, in the C41-A-North water control catchment the operationally significant water bodies account for 0.35% of the catchment area. However, in certain water control catchments the water bodies make up the majority of the catchment area. For example, Lake Okeechobee covers almost 80% of the land designated as the Lake Okeechobee water control unit catchment. Thus the rainfall on a specific operational water body may represent a significant portion of the water flux into the body. On November 17, 2002 the rain area rainfall estimate for Lake Okeechobee was 2.01 inches. Based on that amount of rainfall and a lake surface area of 730 acres, 2.73×10^9 cubic feet of rain fell directly into Lake Okeechobee. In contrast, the measured structure inflows for the same day measured 4.87×10^8 cubic feet of water entering the lake from surface water sources. Thus the rain that fell directly onto the water body was 5.6 times greater than the volume of water that entered through measured structures. In several instances from November 1, 2002 to October 31, 2003 rainfall onto the C41-A-North water control unit was the only recorded water input into the system. For five days at the end of May 2003, rainfall directly on the C41-A-North water control unit was the only recorded flow into the water body, and the following day approximately 5% of the total water entering the water control unit was due to rainfall directly on the water control unit. Therefore, rainfall directly onto water bodies cannot be uniformly ignored in the SFWMD.

Similar to rainfall, evaporation for a water body is generally ignored in many hydrologic calculations; however, in the summer in southern Florida evaporation can amount to 5 mm/day [0.2 in/day]. This amount may sound trivial in general operating terms; however, the amount of water that is lost due to evaporation from large water bodies can be significant. Again, taking an example from Lake Okeechobee, on February 28, 2005 the average pan evaporation rate at two stations in proximity to Lake Okeechobee was 0.18 inches per day. Based on an estimated area of 730 square miles the evaporation out of Lake Okeechobee is equivalent to 3337 cubic feet per second. The water lost due to evaporation is almost 3 times greater than the volume entering the lake through SFWMD operated structures. Thus, it is important to include the water evaporated directly from water bodies in the water balance equation.

To estimate the water surface area for a water control unit in a simple manner it was proposed to use a surface area without variation included. Due to the channelized nature of the water bodies, the surface area of a water control unit does not change significantly with an increase or decrease of water levels. Estimates for water surface area were calculated based on canal geometry found in the feature class Canals. The water surface area for the minimum surface was calculated using the minimum observed water surface elevations at each of the three control points. Conversely, the maximum water surface area was calculated using the maximum water surface elevations at each control point. For example, in the water year 2002-2003 the maximum surface area of the C41-A-North canal was estimated to be just over 5 million square feet, and the minimum surface area was calculated to be 4.9 million square feet, Table 2. The difference between these extremes is 3%. Three percent change in surface area of a water body that covers only 0.35% of the entire water control catchment produces an input of rainfall and evaporation change of 0.1%. Thus a time-invariant water body surface area is sufficient to describe most water bodies of operational significance within the Three Lakes test area.

Table 2 Minimum and Maximum Calculated Surface Areas of C41-A-North Canal from Water Year 2002-2003.

	S68 Tailwater Elevation	S83 Headwater Elevation	S82 Headwater Elevation	Calculated Surface Area [ft^2]	% Difference
Minimum Value	31.44	31.38	31.38	4,919,899	
Maximum Value	32.95	32.12	32.14	5,072,591	3.06

The surface area values used for the calculations within Excel and Arc GIS are based on the feature shape area defined by the operationally significant water bodies within a water control catchment. Querying the C41-A-North water body in ArcGIS, the estimated surface area is 5,286,738 square feet. Comparing the estimated surface area to the measured surface area, there is a 4% difference between the estimates surface area from linear interpolation of canal features and the polygon defining the water body derived from the 24K NHD. Thus the area of the water bodies described by the 24K NHD polygons and deemed operationally significant by the SFWMD's water managers are a good representation of the water body surface area.

3.2.2 Water Balance over a Water Control Catchment

The change in water storage over the water control catchment is calculated in the same manner as the water control unit water balance (Section 3.2.1); however, it is assumed that there are no surface or groundwater flows that enter the water control catchment. The inputs and outputs out of the water control catchment control volume are the rainfall onto the area, the evapotranspiration out of the area and the transfer of water from the land surface to the water bodies. The transmission of water is historically thought of as being from the land surface to the water bodies, thus Q_{TRANS} is negative in the water balance over the water control catchment.

$$\Delta S_{catch} = \left(P_{catch} - ET_{catch}\right)A_{catch} - Q_{TRANS} \qquad \textbf{Equation 20}$$

Areal estimates of precipitation and evapotranspiration are required in order to determine the change in storage within the water control catchment. It is assumed that rainfall and precipitation will generally be much larger over the water control catchment than the movement of water from the water control units to the water control catchments for water control catchments that have small operationally significant water bodies compared to the size of the land surface within the catchment.

3.3 Creating a Hydrologic Flux Coupler

There is no component of the GIS software that creates a link between all the time varying fluxes and flows that enter and leave a control volume. To estimate the change in water stored within a control volume the links between all of the inputs and outputs of the control volume must be known within the GIS data model. To accomplish this task of creating links between the control volume and the fluxes and flows, a software application called the Hydrologic Flux Coupler is proposed. The idea behind the Hydrologic Flux Coupler is an explicit representation of the movement of water, energy, or mass relative to a particular control volume. Each control volume is considered independent of every other control volume and the movement between any control volumes is known (i.e. can be modeled or measured). Each control volume is a discrete feature within the data model that interacts with time varying inputs and outputs. To link the movement of water, energy, and mass to the control volume, a table feature within the data model called a Coupling Table is used to summarize the water, energy, or mass movements. The Coupling Table defines the measured or modeled fluxes and flows that interact with the control volume and the associated direction of flow or flux. There is the potential for the movement of water, energy, or mass to be into or out of, depending on the specific type of analysis. To capture changes in flow direction a negative sign in the Arc Hydro time series table indicates that the movement of water, energy or mass is in the opposite direction stated in the Coupling Table.

Once the known fluxes and flows associated with a control volume are included within the Coupling Table, it is possible to use the Hydrologic Flux Coupler software to estimate the water, energy, or mass balance associated with a distinct feature in the data model. For the Hydrologic Flux Coupler to work, the control volumes must be identified. For the study conducted for the SFWMD there are two types of control volumes of interest, the water control units and the water control catchments. Both types of control volumes have inputs and outputs that are spatially and temporally variable, such as rainfall. However, the Hydrologic Flux Coupler and the water managers within the SFWMD are concerned for the movement of water only between separate water control units and the movement of water between a water control unit and the associated water control catchment. Thus the water control units and the water control catchments are considered lumped or buckets in which water is either transported or stored over a given time period of interest. It is assumed that both types of control volumes can store water over a given time period.

3.3.1 Coupling Table Format

To compute water, energy, or mass balances within Arc GIS over a specified control volume the flux or flow and the direction of movement must be known. To successfully represent the fluxes and flows into and out of a control volume and express the direction of water, energy, or mass movement, the Coupling Table must document these characteristics. The format of the Coupling Table includes the feature ID of the control volume of interest, generally a polygon feature, the common name of the feature; the feature associated with the flux or flow, such as a polygon, line, or point; the common name of the feature; the TSTypeID, which describes the type of measurement the feature is associated with; and finally, the direction of the flux or flow movement, Figure 20.

Attributes of COUPLINGTABLE

FeatureID	FeatureCode	SourceSinkID	SourceSinkCode	TSTypeID	Direction
104552	Lake Kissimmee - Waterbody	79979	S65	1	2
104552	Lake Kissimmee - Waterbody	184374	Upper Kissimmee rainarea rainfall	2	1
104552	Lake Kissimmee - Waterbody	184374	Evaporation	3	2
120154	S65A - Waterbody	79979	S65	1	1
120154	S65A - Waterbody	79981	S65 A	1	2
120154	S65A - Waterbody	184375	Lower Kissimmee rainarea rainfall	2	1
120154	S65A - Waterbody	184375	Potential Evaporation	3	2
120154	S65A - Waterbody	120154	Qtransmission	6	1
150024	S65A	184375	Lower Kissimmee rainarea rainfall	1	2
150024	S65A	184375	Evapotranspiration	7	2
150024	S65A	150024	Qtransmission	6	1
150001	S65BC	184375	Lower Kissimmee rainarea rainfall	1	2
150001	S65BC	184375	Evapotranspiration	7	2
150001	S65BC	150001	Qtransmission	6	2
120193	C41-A-North	79985	S68	1	1
120193	C41-A-North	79986	S82	1	2
120193	C41-A-North	79987	S83	1	2
120193	C41-A-North	184375	Lower Kissimmee rainarea rainfall	2	1
120193	C41-A-North	184375	Potential Evaporation	3	2
120193	C41-A-North	120193	Qtransmission	6	1

Record: 1 Show: All Selected Records (0 out of 20 Selected.) Options

Figure 20 Example of Coupling Table structure and data

The columns FeatureID and SourceSinkID are the HydroID values of the features associated with the control volume feature and the source or sink of interest, respectively. The SourceSinkID is used to search through the time series tables to determine the appropriate value of the source or sink into or out of the control volume for a time step (an interval of time within the time series). The FeatureCode and SourceSinkCode are equivalent to the HydroCode property in the standard Arc Hydro framework; the code is the common name of the feature and is not used in any calculations or queries for the Hydrologic Flux Coupler. TSTypeID refers to the measurement types described in the Arc Hydro formatted TSType table. The direction of flux or flow has been defined so that (1) represents movement into the control volume and (2) represents flow out of the control volume. Each flux or flow is represented by a single entry in the Coupling Table.

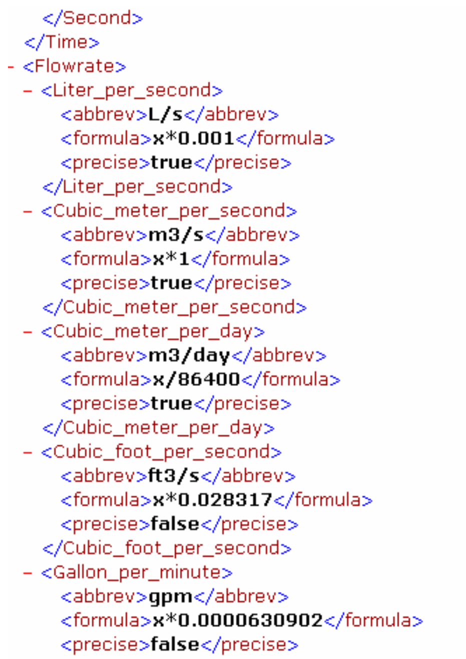
3.3.2 Calculating Volume of Water Movement

The units of fluxes and flows are mathematically different, the units of flux are expressed in units of volume per area per unit time, and where as the units of flow is expressed in units of volume per unit time. To combine the two measurement types into a single unit of measure a conversion process is required. The units of volume per unit time are used to express the movement of water into, out of, and between control volumes. As mentioned previously there are three types of water movement in a hydrologic sense, a point flow, a line flux and an area flux. All three of these measurements can be converted into a volume per unit time using a multiplication factor.

Table 3 Units of measure for hydrologic fluxes and their multiplication factors

Measurement	Units	Multiplication Factor	Resulting Units
Point Flow	L^3/T	-	L^3/T
Line Flux	L^2/T	L	L^3/T
Area Flux	L/T	L^2	L^3/T

Based on the idea that each measurement type must be converted into a volume of water being transferred into or out of a control volume the Hydrologic Flux Coupler uses these multiplication principles to convert the measurement type into a volume of water. The Hydrologic Flux Coupler uses a controlled vocabulary contained in an XML file to determine the measurement type that the TSTypeID is, whether it is an area flux, a line flux or a point flow, Figure 21.



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  </Time>
- <Flowrate>
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    </Cubic_foot_per_second>
  - <Gallon_per_minute>
      <abbrev>gpm</abbrev>
      <formula>x*0.0000630902</formula>
      <precise>false</precise>
```


Figure 21 XML File containing controlled vocabulary for Hydrologic Flux Coupler

The Hydrologic Flux Coupler program algorithms are used to determine the if type of measurement is flux, then the program will carry out the appropriate multiplication factor to estimate the total volume of water that enters the control volume due the flux or flow. If the measurement is associated with a point, then it must be a flow measurement as a point does not have area for converting a flux to a flow. Thus, it is important to ensure that a flow is associated with a point measurement, a line flux is associated with a line and an areal flux is associated with area. The Hydrologic Flux Coupler uses the length or area of the line or area to convert the flux into a volume of water over a selected time period. As shown in Figure 22, the Hydrologic Flux Coupler uses the geometry of the feature associated with a measurement type to convert the measurement from either a flow or flux into a volume of water.

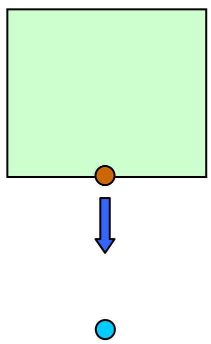
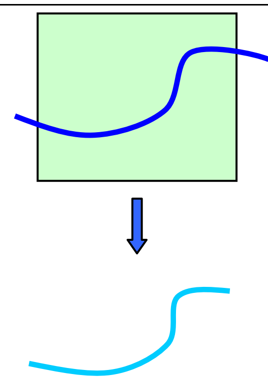
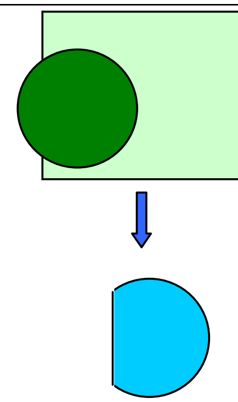
Point Flow	Line Flux	Area Flux
		
-	Line	Area

Figure 22 Conceptual drawing on multiplication factors for estimating volume of water entering a control volume

In the Arc Hydro time series model there are four types of measurements: instantaneous, average, cumulative, and incremental (Figure 23). There are two other measurement types defined in the Arc Hydro data model that are of minimal importance to this analysis, maximum and minimum time series measurements, which will not be discussed. For the majority of the analysis within this document, the time series data type being used is an average time series, such as a daily flow measurement. The average measurement type is used for flow information, where an average daily flow is reported for a given structure over a given day.

$$\overline{Q}(t) = \frac{\Delta V}{\Delta t} \qquad \textbf{Equation 21}$$

On the other hand, precipitation or potential evapotranspiration is an incremental time series measurement where the data are accumulated for the entire time period. A reported value of 1.00 inch of rain over a day is an incremental value. One inch is not a value that represents the rainfall at any particular instant in time, but the accumulated measurement of rain measured over the given time period. This is different than the average time series value which, again, does not represent a single instant in time, but rather represents an average value that represents the average flow over a single time period, such as a single day. To represent daily flow in a similar manner as the rain data, the information must be in the same units: volume or length. This can be accomplished by multiplying the average time series value by the length of the time period of interest the incremental value is obtained.

$$\Delta V = \int_{*t}^{*t+\Delta t} \overline{Q}(t)dt \qquad \textbf{Equation 22}$$

The information processed by the Hydrologic Flux Coupler is computed using the incremental time series information type. Thus, if the information in the Coupling Table is an average value, the time series is multiplied by the length of the time step to calculate the incremental volume. If the information in the Coupling Table is an incremental value the time series is multiplied by either the length or area of the feature to calculate the incremental volume over the given time period.

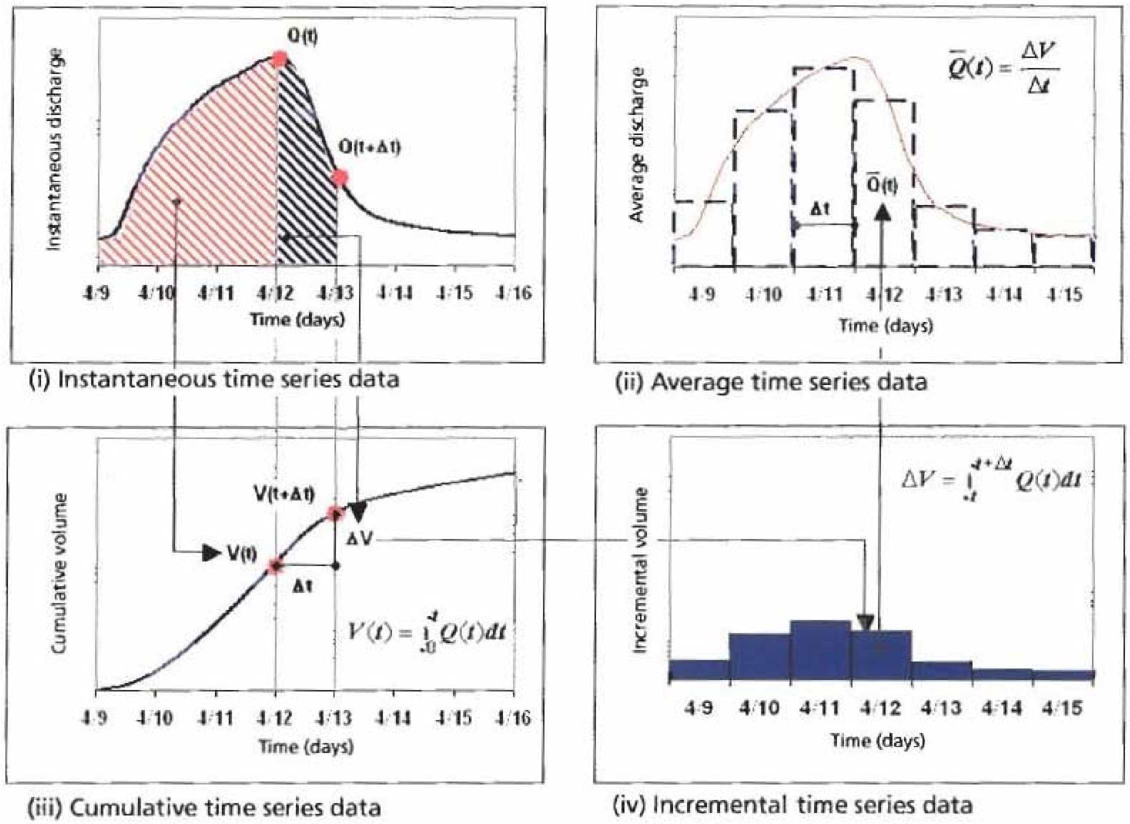


Figure 23 Description of Four Time Series described in the Arc Hydro Time Series Model

A difficulty arises when using the Hydrologic Flux Coupler with real-time information as input data, the majority of flow data is instantaneous rather than average time series information. Thus, the conversion of information into an incremental time series measurement is slightly different. To estimate the total amount of water that passes through a structure over a given time period, the instantaneous value at time t must be known, and the instantaneous value at time t+Δt, where Δt can be of varying lengths. The volume of water passing through a structure of the time period Δt is:

$$\Delta V = Q(t) \cdot \Delta t \qquad \textbf{Equation 23}$$

Where Q(t) is the flow rate measured at the instant t, which is valid over the time period Δt.

3.4 Rainfall Estimation

There are multiple methods to estimate areal precipitation rates, see Section 2.2, whether from point data information or from NEXRAD radar estimates. Areal estimates of precipitation and evapotranspiration are required to determine the change in storage within the water control catchment. For water control catchments , it is assumed that rainfall and precipitation will generally be much larger over the water control catchment than the amount of water moving between the water control units and the water control catchments.

3.4.1 Gages

There are 69 OMD rainfall gages monitored regularly by water managers and operators at the SFWMD that have rainfall information associated in DBHydro and documented spatial locations in the shapefile Stations. The majority of the OMD rain gages are located around Lake Okeechobee, the agricultural regions south of Lake Okeechobee, and in the Miami-Dade region. There are a few OMD rain gages in less populated areas, such as the Everglades National Park. Twenty-five OMD rain gages are contained inside of or are within one mile of the Three Lakes test region, Figure 50.

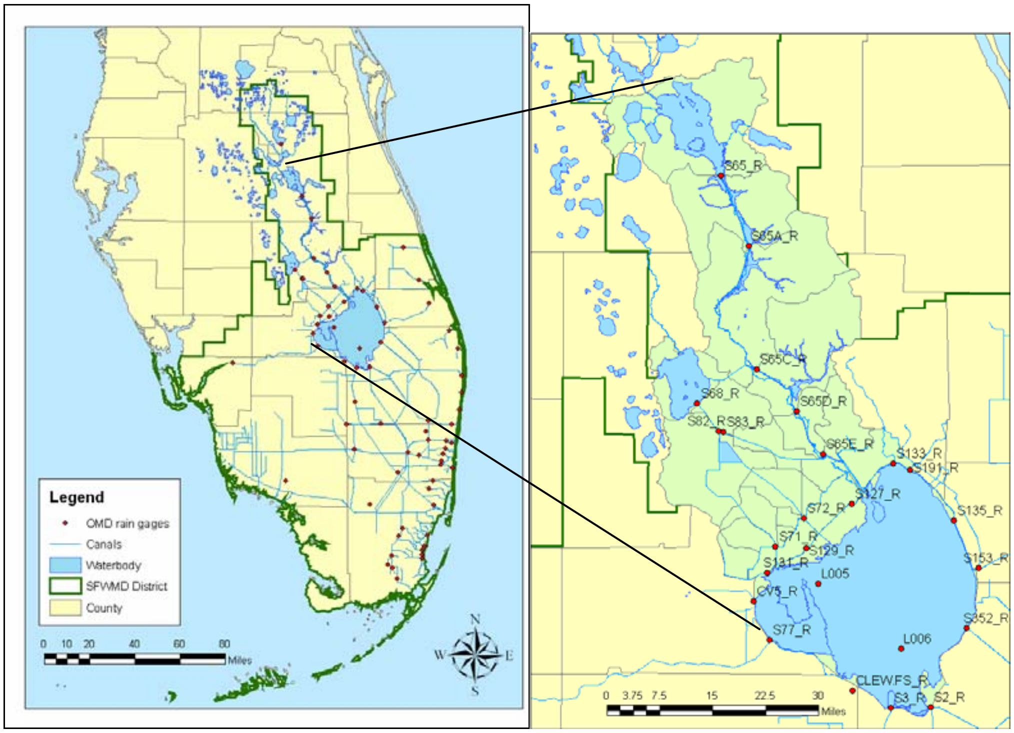
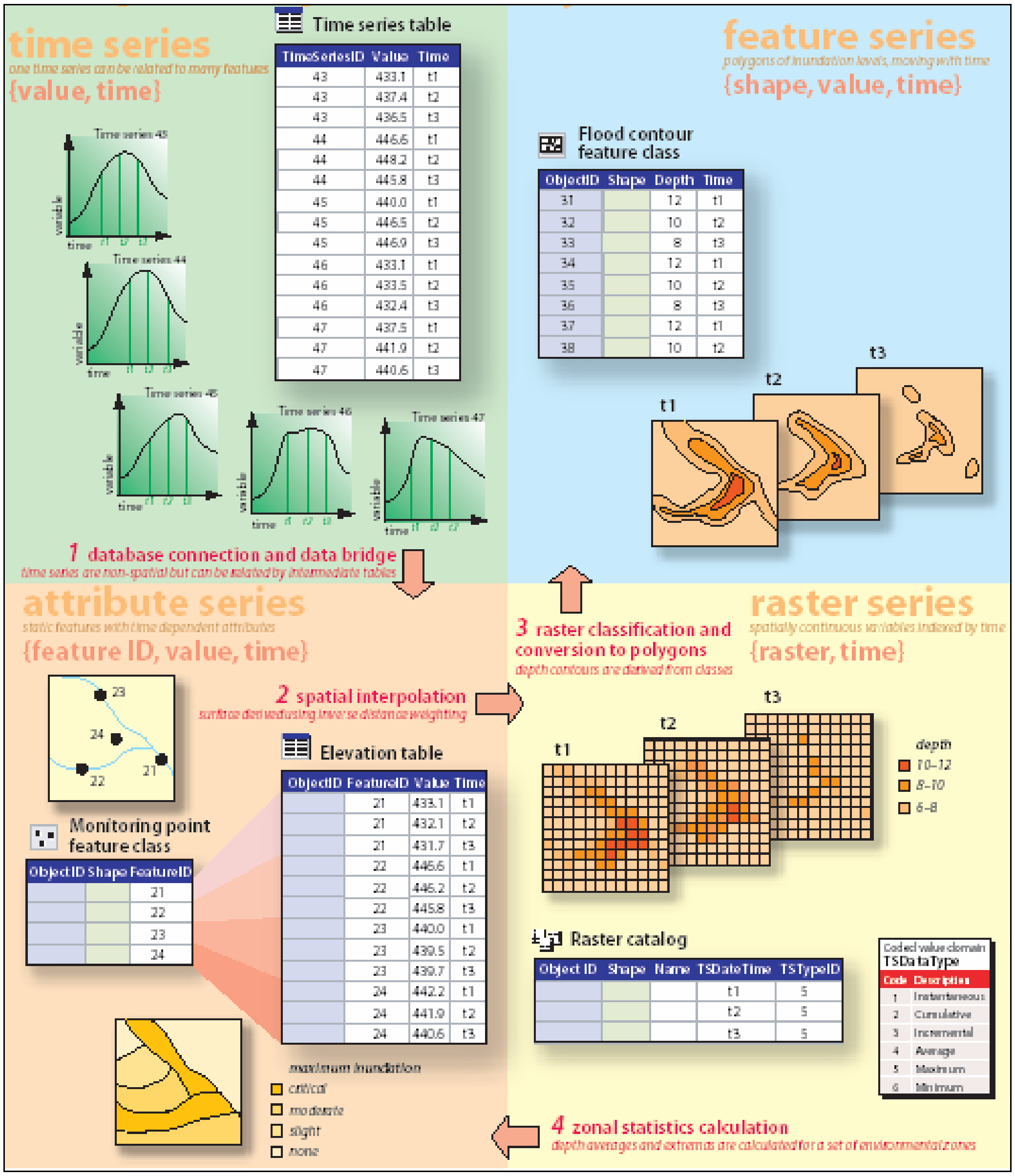


Figure 24 OMD rain gages for SFMWD and detailed view of Three Lakes test area

Since the OMD rain gages are currently being used by water managers and operators of the SFWMD, these gages an initial data set for analysis of point rain gage information to estimate areal precipitation rates. Within the C41-A-North water control catchment there are three OMD rain gages, S68_R, S82_R, and S83_R identified by DBKey identifiers 16654, 19655, and 16656. The rainfall measurements recorded in the DBHydro database are assumed to be correct; they are quality assured and quality control by the SFWMD before they are placed in the database. No additional calculations were conducted on the rain gages unless the areal estimation technique being used required a calculation.

3.4.2 NEXRAD

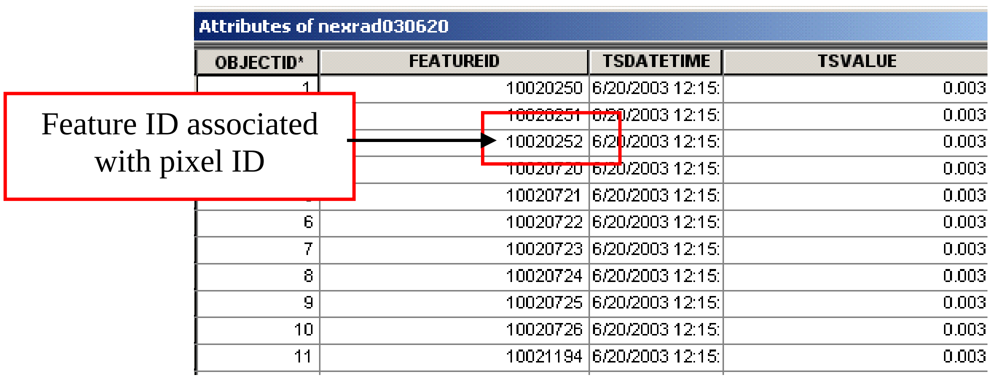
As described in "Designing Geodatabases" (Arctur and Zeiler, 2004) there are four types of temporal-spatial data sets: time series, feature series, raster series, attribute series. The difference between the data types is described in Figure 25. A time series data set is the data format prior to association with a spatial feature. In this analysis, information described by a time series would be equivalent to information stored in the DBHydro database. That is, it is not associated with a spatial feature, but describes a time series of information. Once the information is imported to the Arc Hydro time series format, the information is considered an attribute series. The information not only includes the time series information, but also the associated spatial feature. For example, a structure does not change its shape or location, thus any time series information associated with the structure in the Timeseries table in Arc Hydro is an attribute series. Or, in the case of NEXRAD rainfall analysis, time series information associated with a pixel ID is considered an attribute series. To use the spatial analyst utilities of GIS, the pixel ID attribute series is converted from an attribute series to a raster series. The raster series describes a time varying raster, which has constant dimensions but varying values in time. In the case of estimating areal rainfall rates over a water control catchment, the raster series utilizes zonal statistic tools within Arc GIS to calculate another time varying attribute series, this time associated with the water control catchments and not individual pixels in the NEXRAD rain mesh. No feature series are used in this analysis; however, if a polygon feature of the rainfall contours was constructed, which varies in space and time, then a comparable feature time series is constructed. The example of all of the time series developed in Figure 25 was for inundation depths for the SFWMD.



From Arctur and Zeiler, 2004

Figure 25 Four types of temporal and spatial data within Arc Hydro data frame

To link rainfall and water volumes on the land surface, the spatial rainfall recorded from NEXRAD radar sources was used to estimate the volume of water that fell in each water control catchment within the Three Lakes test area of the SFWMD. Rainfall information used in the Three Lakes test area of the SFWMD is collected in two fashions: rain station gages on the ground, and next generation radar data (NEXRAD). The most comprehensive spatially and temporally varying of the two is the NEXRAD data. An initial analysis of the computing time and spatial variability associated with raster cell size variation was undertaken. The information used for this first analysis was 15 minute rainfall data over a 24 hour period. The second analysis of NEXRAD rainfall data was a full-scale analysis of daily rainfall estimates from NEXRAD over the time period of analysis November 1, 2002 to October, 31, 2003 over the Three Lakes test region. In both analyses, the time series information was collected from SFWMD, in text file format, and converted into Arc Hydro Timeseries format; the FeatureID identifies the NEXRAD rainfall grid that the value is associated with, Figure 26. This portion of the data conversion is the conversion of time series information to attribute series.


Attributes of nexrad030620

OBJECTID*	FEATUREID	TSDATETIME	TSVALUE
1	10020250	6/20/2003 12:15:	0.003
	10020251	6/20/2003 12:15:	0.003
	10020252	6/20/2003 12:15:	0.003
	10020720	6/20/2003 12:15:	0.003
	10020721	6/20/2003 12:15:	0.003
6	10020722	6/20/2003 12:15:	0.003
7	10020723	6/20/2003 12:15:	0.003
8	10020724	6/20/2003 12:15:	0.003
9	10020725	6/20/2003 12:15:	0.003
10	10020726	6/20/2003 12:15:	0.003
11	10021194	6/20/2003 12:15:	0.003

Figure 26: NEXRAD Data stored in Arc Hydro Time Series Format

The value stored in the table is a Stage III NEXRAD estimate of the amount of rainfall that fell in a particular rainfall grid over a 15-minute interval, based on the NEXRAD observations. There are over 33,000 NEXRAD pixels covering the entire SFWMD. If the original analysis were conducted over this region it would take au unknown amount of time; the text file of a year of data for the entire SFWMD is nearly 6 megabytes! Thus, the Three Lakes test region is used for this analysis, there by narrowing the scope of the analysis from 33,000 pixels to approximately 1,900 pixels. The Three Lakes test area is approximately 130 miles by 30 miles [210 km by 48 km] which contains approximately 1900 NEXRAD rainfall grids within it, Figure 27. The NEXRAD grid is approximately 2 km by 2 km. Each pixel is not exactly 2 km by 2 km due to the projection used to display information in the Three Lakes test area.

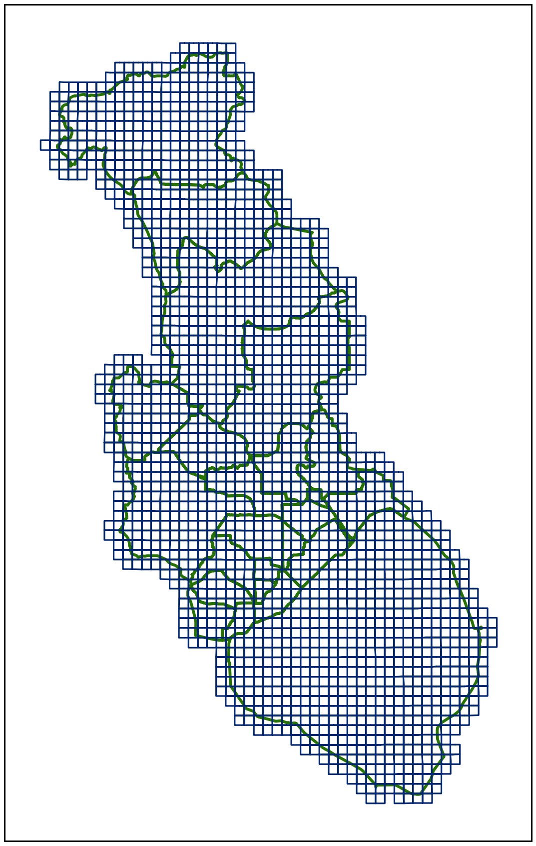


Figure 27: NEXRAD rainfall grid over Three Lakes test area

3.4.3 Optimizing Grid Size Resolution

At a 2 km resolution the grid is much coarser than the basin boundaries located within the Three Lakes Test Region. Therefore, when zonal statistics are used to calculate the amount of rainfall that fell within a basin during a 15-minute or 24-hour period the estimates are very rough. In ArcGIS, Zonal statistics assigns each raster cell to one water control catchment; therefore, if large raster cells are used and there is a large amount of overlap between two adjacent basins, then the volume estimates for one basin will be high than the actual volume, and lower for the other basin, Figure 28. The actual volume of rainfall associated with one basin is assumed to be the volume of water associated with an infinitesimally small grid size. However, practically, the amount of processing time required to create such a raster is prohibitive and therefore an approximation of an infinitesimal raster cell is required. In order to determine the optimal raster cell size for rainfall volume approximation a number of raster cell sizes were tested. A decrease in the raster cell size does not increase the resolution of the rainfall data; rather, a decrease in the raster cell size increases the accuracy of rainfall volume estimates over each basin.

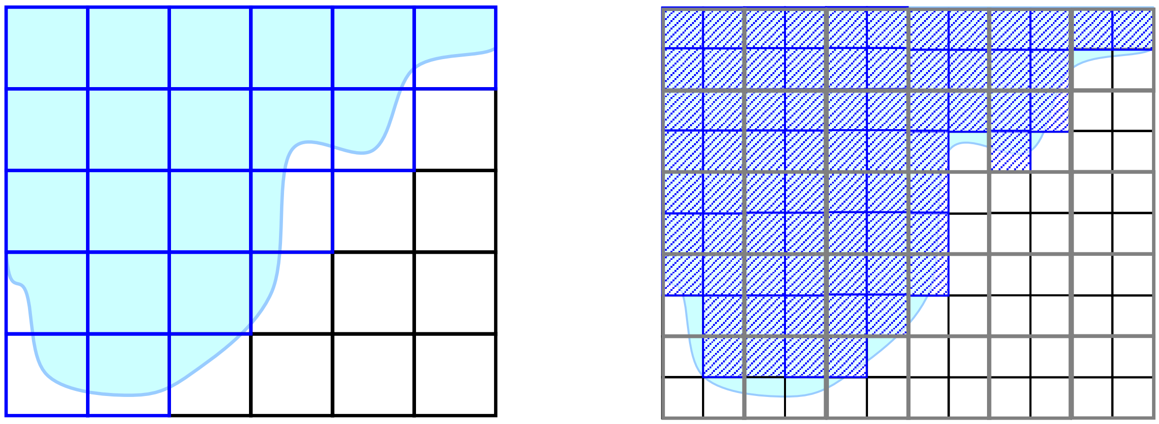


Figure 28: Impact of Grid Size on Grid delineation for Zonal Statistics

Eleven different raster cell sizes were tested, in order to determine the optimal cell size. The definition of the optimal cell size, in this case is: a steady estimate for rainfall volumes per water control unit basin and reduction in the amount of processing time required, signified by the largest possible grid size. It is assumed that as the grid size decreases, the volume estimate approaches the actual answer; in this case the ‘actual’ answer is assumed to the volume total calculated using a 5-meter grid. Thus, all other values calculated are compared to the volume totals calculated using this 5-meter grid. To calculate the volume of water entering each basin due to rainfall the size of the raster rainfall grid must be known. The zonal statistics function produces a total sum of rainfall within a basin over one time step. As shown below, the sum of rainfall values multiplied by the area of the grid will produce the volume of water that fell in the basin over one time step.

$$Volume = A_1 r_1 + A_2 r_2 + A_3 r_3 + \ldots + A_n r_n$$ **Equation 24**

$$Volume = A(r_1 + r_2 + r_3 + \ldots + r_n)$$ **Equation 25**

Summarized in Table 4 are the results of the eleven different grid sizes tested, the size of the grids range from 2000 meters, the size of the NEXRAD grid, to 5-meters. The percent difference is the average percent difference the smallest raster cell size and the raster cell size of interest for all water control catchments in the Three Lakes test area. The maximum difference is the maximum observed difference between the rainfall estimates derived using the smallest raster cell size, 5 meters, and the raster cell size of interest for all water control catchments in the Three Lakes test area.

Table 4: Summary of Grid Sizes Tested during Experiment

Grid Size [m]	Grid Size [ft]	Percent Difference [%]	Max Difference [%]
2000	6560	12,204	198,738
1000	3280	13,000	217,230
500	1640	3.971	25.961
250	820	1.244	4.701
100	328	0.776	4.162
75	246	0.393	1.340
50	164	0.157	0.692
30.5	100	0.094	0.356
25	82	0.080	0.296
10	32.8	0.029	0.103
5	16.4	-	-

The largest grids under consideration, 2000 m and 1000 m, produce volumes estimates that were significantly different than the rainfall volume estimate for the 5-m grid. The coarseness of the grids produces volume estimates that are highly variable between water control catchments, with both extremely high volume estimates and extremely low volume estimates seen in the analysis. Due to the significant percent difference between the volume estimates for these two grids, compared to the much smaller grids, these two grids will not be plotted. Plotting the percent difference between each grid versus the 5-m grid volume estimate the following graph is produced.

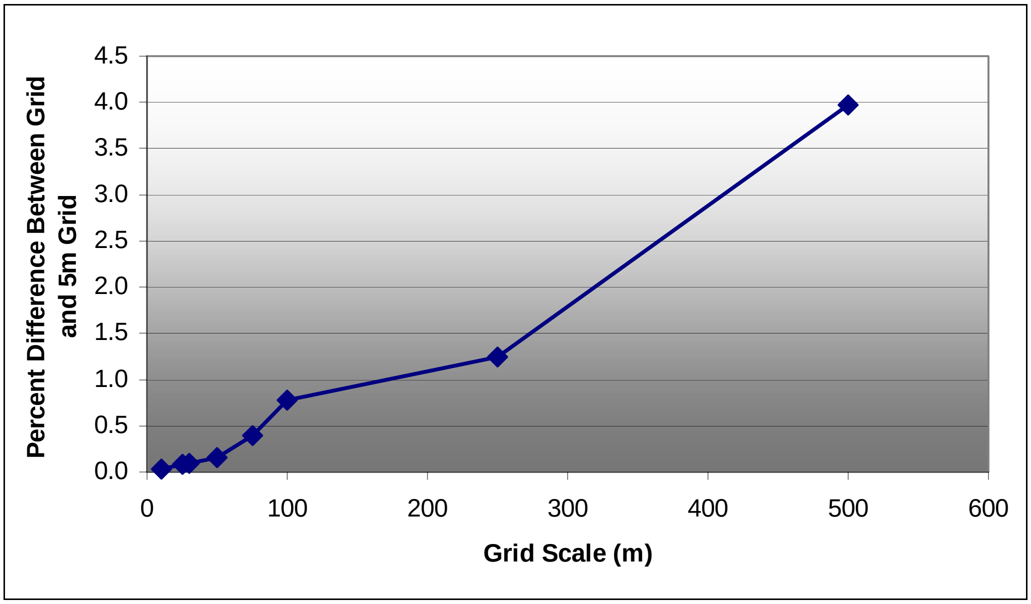


Figure 29: Percent Difference in Rainfall Volume Estimates based on Grid Size versus 5-m Rainfall Grid

As shown in Figure 29, the percent difference between grid sizes asymptotically approaches zero as the grid size approached the 5 meter grid size. However, once the grid size is above 100 m there is a fairly linear relationship between the grid scale size and the percent difference of the volume estimate. Ideally the percent difference between the grids should reach zero at some point; however, an average percent difference of less than one percent would reduce the error associated with the rainfall volume estimates, while still keeping the size of the files, at a single time step, to a manageable level.

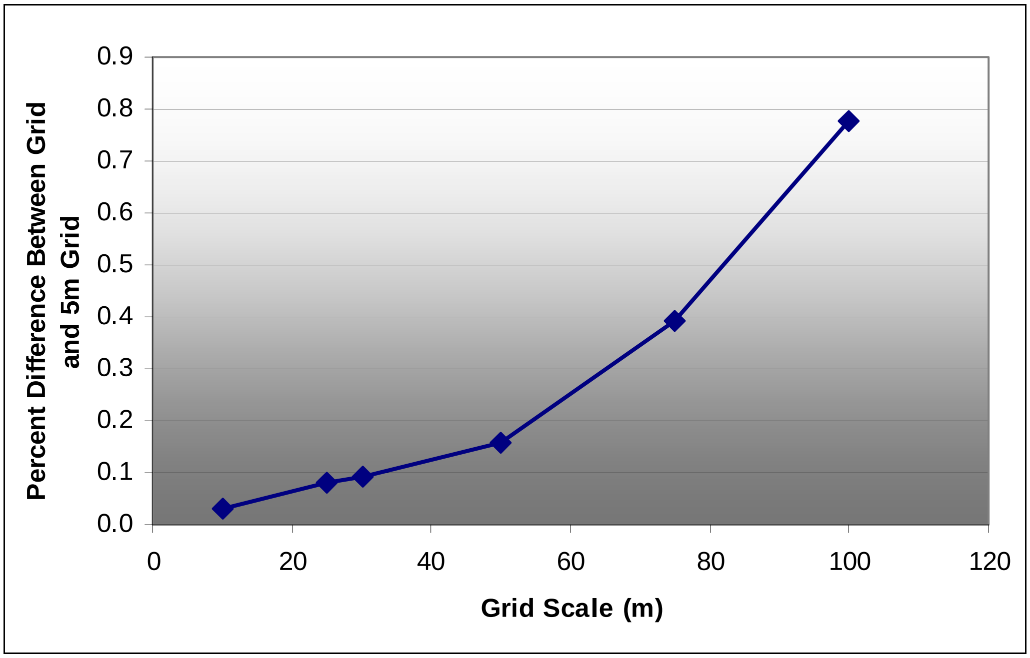


Figure 30: Detailed view of percent difference between volume estimates based on grid sizes less than 100-m versus volumes estimates for rainfall grid of 5-m.

The size of the files stored for each rainfall grid is dependent on the size of the grid, the smaller the grid, the more points of information that are stored in the file, thus, the lowest possible file size would be desirable. Plotting grid size versus file size on a log-log graph the resulting graph is a straight line, Figure 31. Therefore, using the largest possible raster cell size to estimate rainfall volumes is desired, in order to save file space.

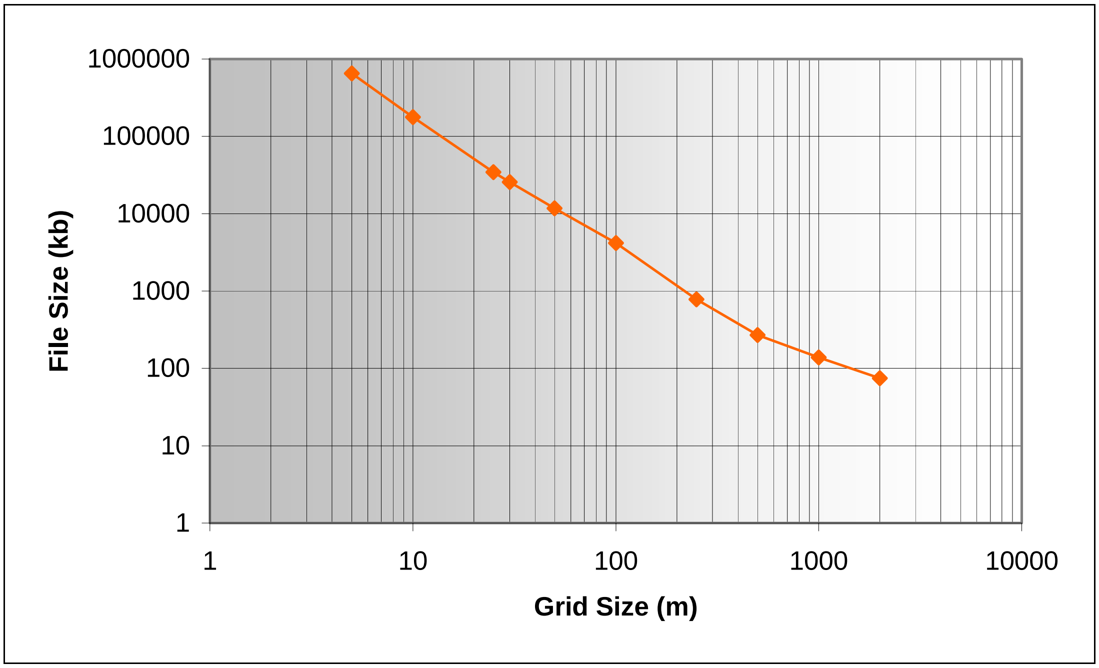


Figure 31 Grid size versus file storage size for rainfall grids between 2000-m and 5-m in size

3.4.4 Optimizing Grid Size and Processing Time

As shown above, the grid size used to calculate rainfall rates can have significant impact on the areal estimate for a water control unit. However, the initial analysis was for a single time step, in a real-time system there must be a looping option available to track changes in precipitation from one time period to another. In the case of looping through several time series, historic data for a one year time period is an excellent opportunity to test analysis techniques. There are 365 time steps in most years, 366 in leap years, if a daily time step is considered then there are a potential of 365 time steps for analysis within the data set. Between November 1, 2002 and October 31, 2003 there were 354 days with at least NEXRAD grid that recorded a daily rainfall value. In the text files received from SFWMD, if no information was recorded for a pixel at a given time period then no value was recorded, this minimizes the size of the data file that is stored. The process of converting the attribute series stored within the Arc Hydro data format to an attribute series associated with the water control catchments in the Three Lakes test area starts with the pixel data in the Timeseries table. The attribute series is joined with the polygon feature class that describes the projection of the NEXRAD cells. Once the time series information is joined to the polygon feature class the feature series is converted into a raster series for the time step. The size of the raster cells is determined when the program is started. In this analysis, three sizes of NEXRAD grids were selected: 500 m by 500 m, 250 m by 250 m, and 100 m by 100 m. The next step in processing the data was the use of zonal statistics within Arc GIS. Using the Spatial Analyst toolbar features zonal statistics were calculated using the water control catchments as the area of interest. The zonal statistics for each water control catchment for each time step was then written into an attribute series contained within the Timeseries table. The temporal and spatial processing for NEXRAD cells is shown in Figure 32.

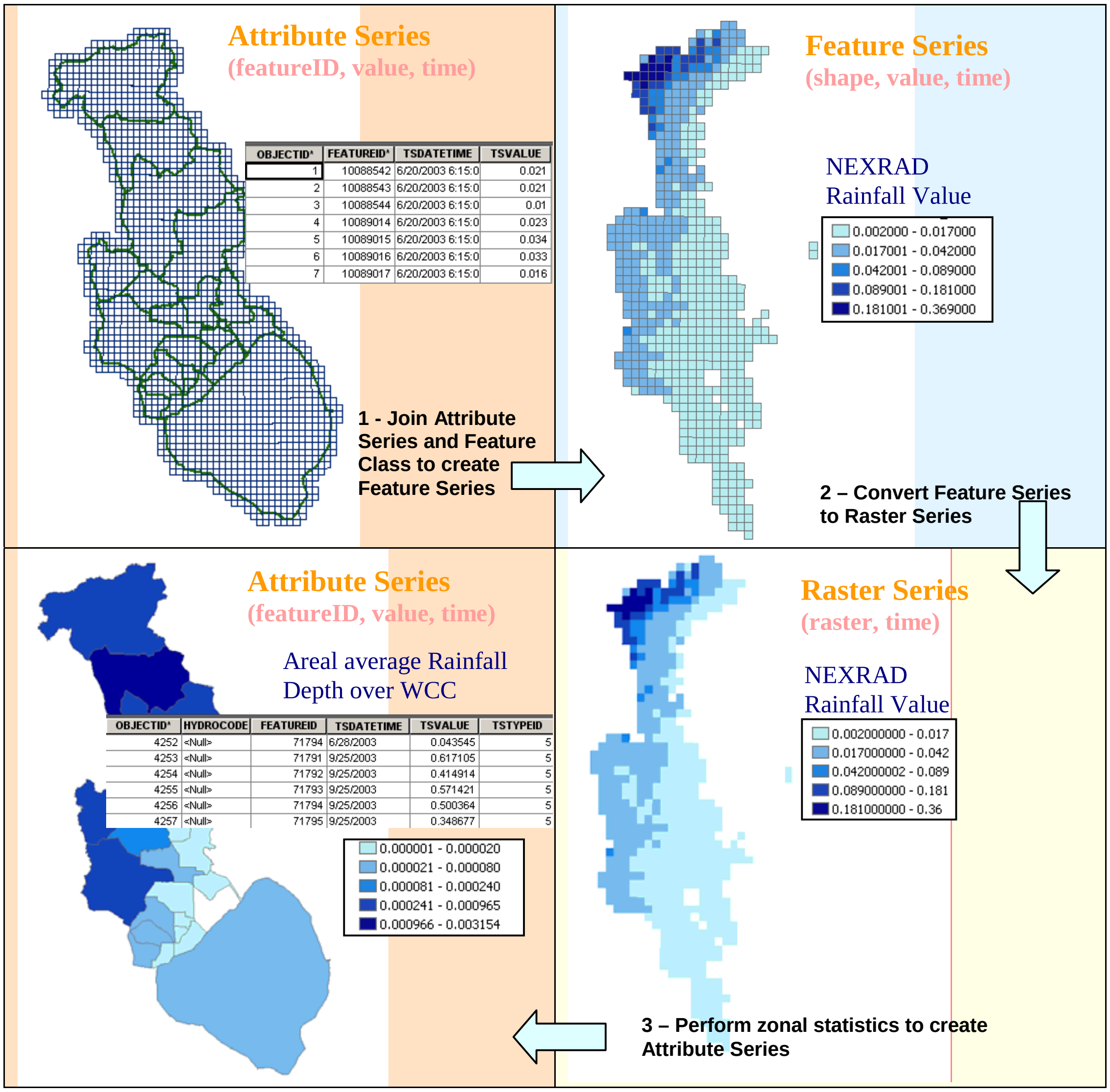


Figure 32 Temporal and Spatial processing of NEXRAD pixel rainfall information to areal average rainfall estimates

Based on the analysis of raster cell size on the rainfall estimate for a water control unit the optimal cell size for rainfall accuracy, compared to an 5 m raster cell size, and the amount of computer storage required the recommended cell size is 100 m; however, based on the analysis for processing time in Section 3.4.2 the optimal grid size for a reasonable processing time is 500 m.

3.4.5 Rain Areas

As mentioned previously, there are fourteen rainfall rain areas within the SFWMD, Figure 4. The information presented to CRWR by the SFWMD was assumed to be correct and no additional processing of the data was done.

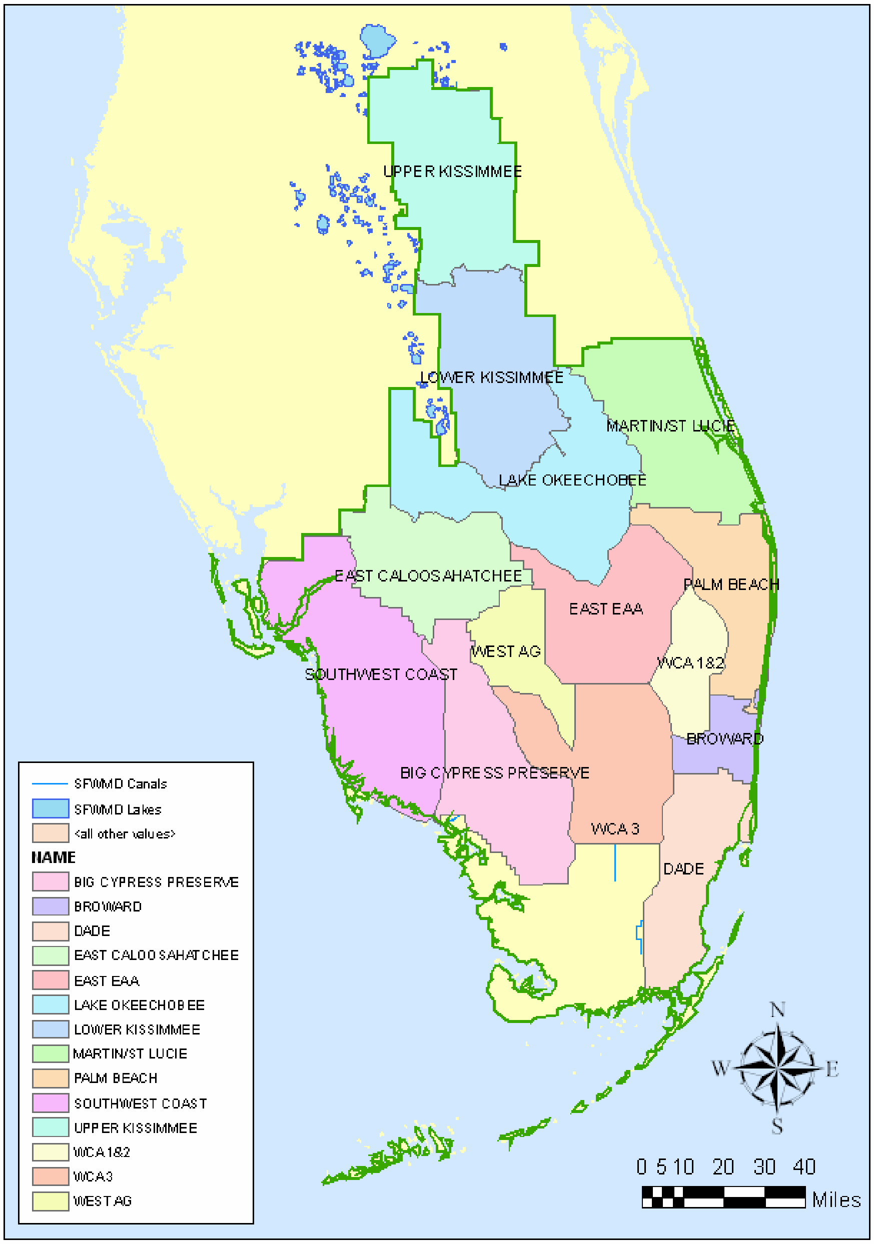


Figure 4 Fourteen Rain Areas covering South Florida Water Management District

3.5 Estimating Waterbody Storage

To calculate the movement of water between the water control units and the water control catchments, the change in water storage within a water control unit must be determined. Since the water bodies making up the water control units are monitored for stage values and documented in terms of canal geometry and canal length, it is possible to directly estimate the volume of water stored. In the initial water balance analysis, it was assumed that the water surface was a linear function between all points in a water body. This assumption was based on the small change in water surface elevation over the long canal lengths. For example, the average difference in water surface elevation between the average tail water elevation at structure S68 and head water elevation at structure S83 in the C41-A-North water control catchment is approximately 0.14 feet, with an estimated distance between the two structures of 33,500 feet for an estimated water surface slope of 4.12×10^{-6} ft/ft. However, this analysis is not hydraulically grounded, thus another member of CRWR conducted an analysis to determine the best method to determine the storage within a water control unit.

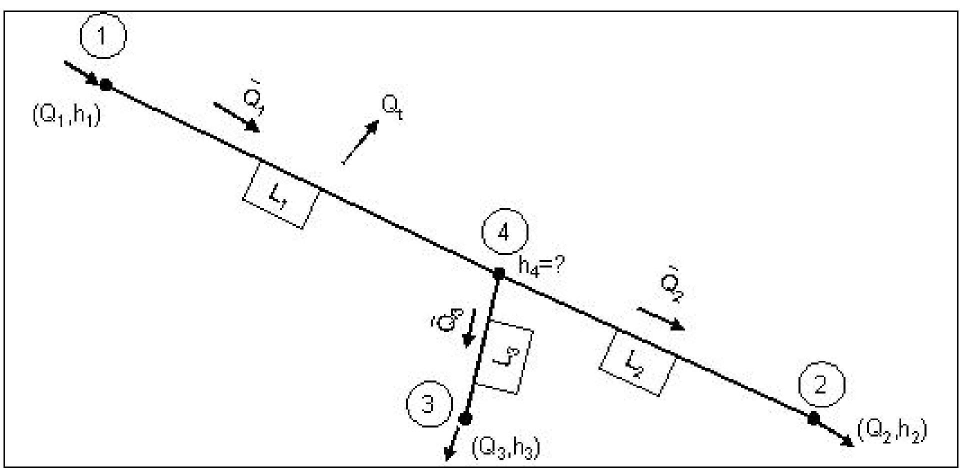
The most important aspect to determine the storage held within the canal water bodies is determining the water surface elevation; it is assumed that the canal geometry does not change over the time period of analysis. In this case the period of analysis is from November 1, 2002 to October 31, 2003. The water control unit used for analysis was the C41-A-North water control unit which contains one flow inlet and two flow outlets. The most difficult part of the analysis is determining the water surface elevation at the junction within the water control unit. There is a small junction approximately 26,000 ft downstream from the S68 structure, thus the water elevations calculated in the analysis must be continuous: there should be no sharp breaks in the estimate of the water surface elevation. Two methods were examined, a hydraulically-based method and a linear water surface elevation method.

3.5.1 Water Surface Interpolation

To estimate the total volume of water within a water body, two aspects of the water geometry must be calculated: the water surface elevation and the canal geometry. The canal geometry for the SFWMD Three Lakes Area is well known compared to the water surface elevations. Canal geometry information is contained in a personal geodatabase feature class called Canals, which is used to estimate water volumes.

3.5.1.1 Hydraulic Interpolation

The hydraulic interpolation method is based on the continuity equation and the conservation of energy. This method is more representative of the actual hydraulic conditions which exist in the canals being modeled. However, several assumptions are still required in order to estimate the volume of water stored in the canals. First, it is assumed that the system is at a steady-state. Second, Manning's equation is used to express the energy losses over the length of the canal. The canal system for the C41-A-North canal can be represented by a conceptual drawing with linear canal features between all structures.



From Martinez et al., 2005

Figure 33 Conceptual representation of C41-A-North canal system

As stated previously, the canal system can be modeled using the continuity equation:

$$Q_t = Q_1 - Q_2 - Q_3 = \frac{\Delta Vw}{\Delta t} \qquad \textbf{Equation 26}$$

Where $\frac{\Delta Vw}{\Delta t} = 0$ due to the steady-state assumption, Q_t is the volume of water flowing although the length of canal system. The energy equation is then used to estimate the head loss along the each canal segment:

$$h_1 = h_4^1 + \left(\frac{n}{1.49 A_1 R_1^{2/3}} \right)^2 L_1 (\overline{Q_1})^2$$ **Equation 27**

Where A_1 and R_1 are the hydraulic area and hydraulic radius of the canal segment, respectively, L_1 is the length of the canal segment based on shape lengths in the feature class Canals, $\overline{Q_1}$ is the average flow as defined by Martinez et al., 2005, and h_4^1 is the height of the water surface at point 4. Since the water equation at point 4 is the unknown that the system of equations is attempting to solve, the equation is re-arranged to find the value of h_4^1. This yields the equation:

$$h_4^1 = h_1 - \left(\frac{n}{1.49 A_1 R_1^{2/3}} \right)^2 L_1 (\overline{Q_1})^2$$ **Equation 28**

The resulting equations for the remaining two canal segments are:

$$h_4^2 = h_2 - \left(\frac{n}{1.49 A_2 R_2^{2/3}} \right)^2 L_2 (\overline{Q_2})^2$$ **Equation 29**

$$h_4^3 = h_3 - \left(\frac{n}{1.49 A_3 R_3^{2/3}} \right)^2 L_3 (\overline{Q_3})^2$$ **Equation 30**

The system of equations presented above must be solved for each time step in order to estimate the water surface elevation at all points in the canal system. Since there are three estimates for the value of h_4, an average value is used to estimate the true value.

$$h_4 = \frac{\sum_{i=1}^{3} h_4^i}{3}$$ **Equation 31**

The sum of squares was used to reduce the estimation errors. Where the sum of squares errors equation is given by:

$$SSE = \sum_i (h_4^i - h_4)^2 \qquad \textbf{Equation 32}$$

The overall system of equations results in a mathematical problem that requires a Manning’s n value that reduces the SSE value. For more detailed information regarding this analysis please refer to the paper by Martinez et al., 2005. Based on the analysis of the Manning’s n, the overall water surface was determined.

3.5.1.2 Geometric Interpolation

The second method used to estimate the water surface at the junction point in the canal system is a simplified method, which assumed a water surface elevation based on a square distance weighting interpolation method, which is not based on the physical conditions present in the canal. This method is termed the “simplified method” and is solved using the following equation:

$$h_4 = \frac{\sum_{i=1}^{3} \frac{h_i}{L_i^2}}{\sum_{i=1}^{3} \frac{1}{L_i^2}} \qquad \textbf{Equation 33}$$

3.5.2 Estimating Water Volumes

Once the water surface elevations are calculated, the next aspect of the calculations is to estimate the actual volume of water contained within each canal segment. In the Canal feature class, each canal segment is described by the bottom elevation, bottom width, side slopes, and top elevation, all are given in feet above mean sea level for elevations, and in feet for length. Each feature describes the length of each canal segment by the ShapeLength, which is an automatic field populated by the Arc GIS software. To model the relation between the water surface elevations and the canal geometries, two methods of calculations were investigated: direct and indirect estimation.

3.5.2.1 Direct Estimation

The direct estimation method uses the computed water elevations at both ends of a canal segment. Between the two points, linear interpolation is used to estimate the water surface within each canal segment. Once the water elevations are known within a reach the volume of water within each canal segment can be estimated. Assuming that the canal can be estimated with a trapezoidal cross-sectional area:

$$A = \frac{h(b + hs)}{2} \qquad \textbf{Equation 34}$$

Where h is the height, b is the bottom width, and s is the side slope. Taking each canal segment and estimating the overall volume for each canal segment is computed from the equation:

$$Vw = \left(\frac{A^I + A^F}{2} \right) \left(L^F - L^I \right) \qquad \textbf{Equation 35}$$

Where Vw is the volume of water, A^I and A^F are the cross-sectional area at the beginning and end segment, respectively; L^I and L^F are the initial and final canal segment length, which is the total length of the single canal segment. To estimate the total water volume within the water control unit is calculated by adding up each water volume for each segment for all canal segments within a water control unit.

$$Vw = \sum_i Vw_i \qquad \textbf{Equation 36}$$

3.5.2.2 Indirect Estimation

The second method used to estimate the overall volume of water within a canal is termed an indirect method. This procedure is developed on the premise to minimize the computational effort required to estimate the volume of water within a water control unit. Reduction of computational effort is important when dealing with the entire SFWMD, where there are thousands of canals and the computation requirements to accomplish these calculations on a real-time basis could be too intense to make the process time effective. Thus, this alternate method was investigates. The premise behind the indirection method is to assume a reference canal condition, with given stage information that is correlated to water control unit volumes. Thus, changes in the flow and stage conditions are small perturbations of the reference case, which can be approximated to the first order by a Taylor Series:

$$Vw_i = Vw_i^* + \sum_i Bi^* (hi - hi^*) \qquad \textbf{Equation 37}$$

For more information regarding this technique please refer to Martinez et al., 2005.

4 Results

The geospatial water balance technique was initially attempted on a single water control unit and catchment contained within the Three Lakes test region, the C41-A-North water control unit and catchment. There is one structural inlet, S68, and two structural outlets that release water from the water control unit, S82 and S83. The three different aspects of the water balance technique are tested to determine the impact of each data type on the water balance for the C41-A-North area. These trials examine: the method to estimate the volume of water within the water control unit, the methods used to estimate areal precipitation rates over the area of interest, and, the estimation of evaporation and evapotranspiration from the area of interest. All three of these data inputs are necassary to estimate the amount of water stored on the landscape. The estimate of the amount of water stored on the C41-A-North gives water managers an estimate of either the water availability or need within a water control catchment. This information has been determined to be important to the water managers within the SFWMD and a value-added product which is currently unavailable.

4.1 Geospatial Water Balancing over a Single Water Control Unit and Catchment

To calculate the water balance over the C41-A-North, all the inputs and outputs of the water balance must be identified, downloaded, and formatted into the correct Arc Hydro time series format. The initial analysis of the water balance over the C41-A-North water control unit and water control catchment were accomplished using Microsoft Excel spreadsheets and the Hydrologic Flux Coupler software. Both calculation methods were used to ensure the Hydrologic Flux Coupler returned the same numbers as the calculations in the Excel spreadsheets. The results from the Hydrologic Flux Coupler are presently not the same as results from the Excel spreadsheet calculations. Thus, additional programming is required to get the results to the same number.

The water balance for the C41-A-North water control unit and catchment was calculated over a one year time period, from November 1, 2002 to October 31, 2003. All water balance calculations were conducted over this time period unless otherwise stated. The flow information for all structures was complied from the SFWMD's DBHydro database. This database contains "hydrologic, meteorologic, hydrogeologic and water quality data" recorded in the SFWMD (SFWMD, 2005c). These data have been quality assured and quality controlled by SFWMD for accuracy before posting to the database. Each structure was queried from the DBHydro database based on the group name, data type, and frequency. Subsequent queries for additional time series information from the same data point or structure were queried using the unique DBKey identifier. To query the structural flow from the DBHydro database the group name, data type, and frequency were selected from the DBHydro browser menu for surface water and meteorological data. The station name was entered, including % symbols wherever a space or unknown character was thought to occur to maximize the total number of data points returned. The data type and frequency queried were flow and daily, respectively. The resulting queries for structural time series information produced the unique DBKey identifiers. Time series information was downloaded from the DBHydro website and saved onto a local computer drive, where additional processing was completed to convert the time series information into the Arc Hydro time series format.

For the information gathered from the three structures, the cumulative flows were calculated from the average daily flows reported in the DBHydro numbers using the following conversion factor:

$$V_i = \sum_t \overline{Q}_i(t) \cdot \frac{86400\sec}{day}$$ **Equation 38**

Where $\overline{Q}(t)$ is the average daily flow for each structure, i, at time t and 86400 sec/day is the conversion factor to calculate the volume of water passing through a structure per day. The cumulative volume of water passing through the structure is the sum of all volumes over a selected time period; in this case from November 1, 2002 to October 31, 2003. The general units of measure for the water balance analysis are cubic feet, ft^3, unless otherwise stated. This common unit of measure reduces the potential for errors associated with conversion factors. The cumulative inflow for S68 and the cumulative outflows for S82 and S83 are a more visual representation of comparative information rather than strictly the volumes of water passing through the structures at a given time period. The cumulative volumes allow the user to visualize the movement of water through the water control unit while comparing the relative amounts of water moving through each control structure. The cumulative volumes reduce the impact of sudden changes in flow volumes on the visual representation of water movement. As seen in Figure 34, the largest volume of water that either enters or exits the control volume is for structure S68. The volume of water passing through structure S68 is larger than either structure S82 and S83 is representative of the fact that there are two outflows and only one inflow. To determine the cumulative structural inflows to the cumulative structural outflows the cumulative volumes calculated for S68 and the cumulative outflow volumes, from both S82 and S83 were compared, Figure 35. The comparison of the two types of structural flow indicate that there is more water entering the water control unit from S68 than is leaving the structures strictly due to flow from structures S82 and S83, thus the conservation of water mass in the water control units is not represented by the amount of volume passing through the structures at the beginnings and ends of the C41-A-North water control unit.

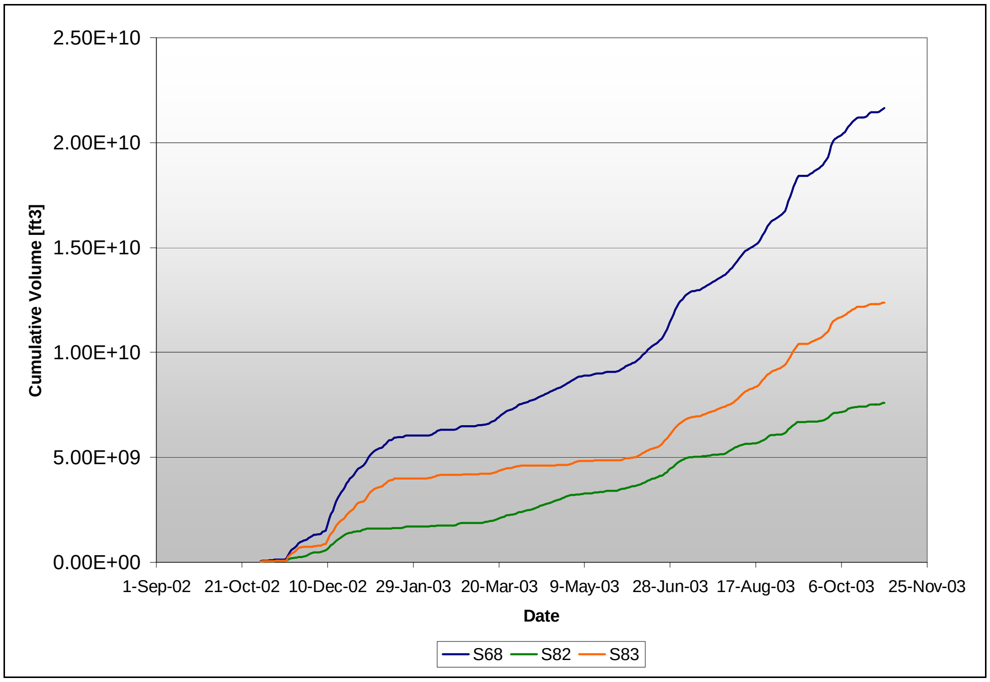


Figure 34 Cumulative Structural Flow Volumes for S68, S82, and S83 into and out of C41-A-North

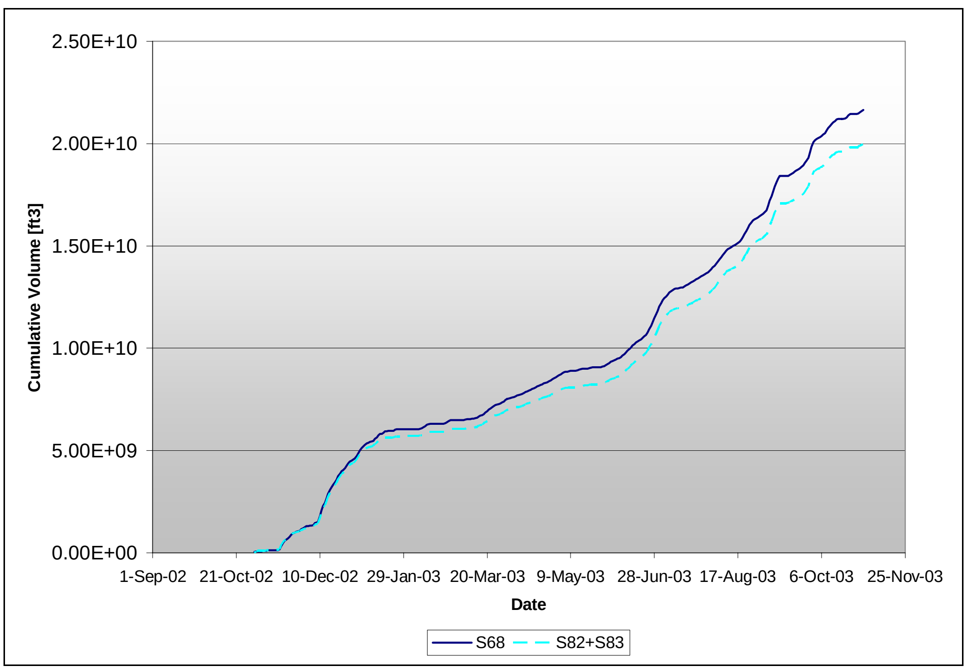


Figure 35 Cumulative Structural Flow Volumes for Net Inflows and Outflows for C41-A-North

As developed in the methodology section, there are other factors that affect the movement of water through a water control unit, including rainfall directly onto the water control unit, evaporation from the free water surface and the movement of water between the water control unit and the associated water control catchment. As shown in section 3 the water balance for the water control units is:

$$\Delta S_{WCU} = Q_{in} - Q_{out} + P_{WCU} - ET_{WCU} + Q_{TRANS} \quad \textbf{Equation 39}$$

Where ΔS_{WCU} is the change in storage from time period t to time period $t+\Delta t$. Q_{in} and Q_{out} are the structural flow into and out of each water control unit, P_{WCU} is the volume of precipitation that falls directly onto the water control unit, ET_{WCU} is the evaporation directly from the water control unit and Q_{TRANS} is the volume of water transferred from the water control catchment to the water control unit. There are several methods to estimate the areal precipitation, the evaporation rate, and the storage change within the water control unit. Thus the following water balance cases are summarized to determine the optimal data sources for the calculation of water balances for each water control unit and water control catchment. The following analysis was not undertaken for the estimation of structural flow. There are currently other projects underway in the SFWMD that are looking at refining the flow estimation equations for all major structures within the SFWMD.

The initial data source for evaporation from the free water surfaces is from the potential evapotranspiration measurements recorded by the SFWMD. There are two potential evapotranspiration measurements recorded in the Three Lakes test region. These data points are located at the S65CW and S65DWX weather stations and are identified by the DBKey numbers OH521 and OH511, respectively. The use of potential evapotranspiration data for the estimation of actual evaporation for a free water body from a water control unit is initially assumed to be more appropriate than a pan evaporation measurement, where the pan coefficient varies through time. (Abtew, 2001) However, additional analysis of additional evaporation data will be considered subsequently. The initial estimate for rainfall is the rainfall measurements recorded at structure S82, which is located near the south side of the C41-A-North water control unit. Measured data estimated across the entire water control catchment and water control unit is initially considered over indirect measurements such as NEXRAD and interpolated data such as the operational rainfall rain areas. The DBKey identifier for the rainfall measurements recorded at structure S82 is 16655. A summary of all the inputs for the water balance over the water control unit is found in Table 5

Table 5 Summary of data inputs and data sources for Case 1a water balance for C41-A-North water control unit

Measurement Type	Station Name	DBKey Identifier
Rainfall	S82	16655
Potential Evapotranspiration	S65CW	OH521
Potential Evapotranspiration	S65DWX	OH511
S68 Tailwater Stage Elevation	S68_T	15957
S82 Headwater Stage Elevation	S82_H	15961
S83 Headwater Stage Elevation	S83_H	15963

The combination of fluxes, flows and stage measurements are combined to predict the volume of water that moves from the C41-A-North water control catchment to the C41-A-North water control unit using the following equation:

$$Q_{TRANS,C41AN,t} = -\left[(Q_{S68,t} - Q_{S82,t} - Q_{S83,t}) + (P_{S82,t} + ETp_{\overline{S65CW+S65DWX}})A_{C41AN} - \Delta S_{WCU,t}\right]$$

Equation 40

Where t is the time period of interest. $P_{S82,t}$ is the rainfall rate from rain gage S82, ETp is the average reported potential evapotranspiration rate reported from the two monitoring stations as S65CW and S65DWX. The average value was reported due to missing data points in each of the time series records. A_{C41AN} is the reported area for the surface area of the water control unit recorded from the 24K NHD data set. The change in canal storage $\Delta S_{WCU,t}$ is calculated based on the change in storage from t-Δt to time period t. The first step in the water balance is to calculate the change in water volume storage within the water control unit, Figure 36. As noted in the figure there is very little change in the volume storage change from day to day, compared to the total volume of water stored in the water control unit.

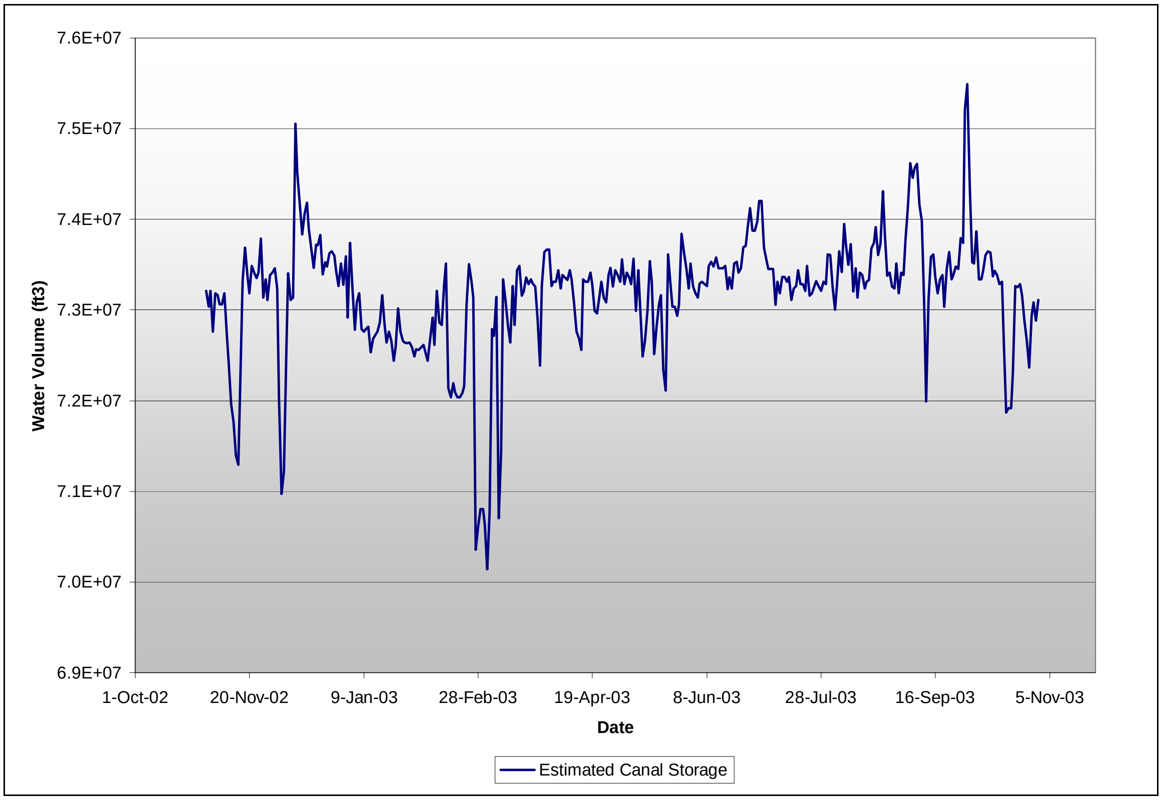


Figure 36 Estimated water control unit storage using linear interpolation for C41-A-North

The change in storage from day to day is computed from the estimated total water volume storage for two sequential days. The results of the change in storage from each time period are found in Figure 37.

$$\Delta S_{C41AN,t} = S_{C41AN,t-\Delta t} - S_{C41AN,t}$$ **Equation 41**

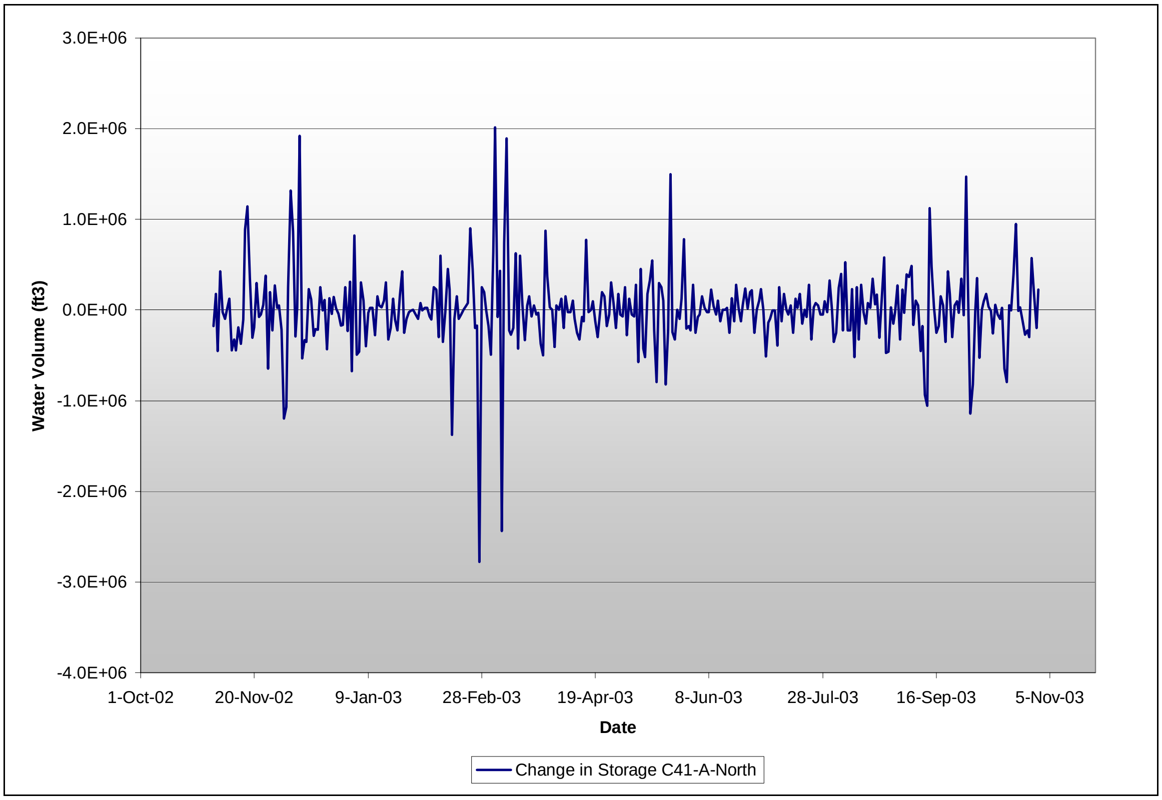


Figure 37 Estimated change in water control unit storage for C41-A-North using linear interpolation

Once the change in storage is estimated, it is possible to use the information gathered to estimate the amount of water transferred between the more monitored water control unit and the less monitored water control unit catchment. The estimates for Q_{TRANS} for the C41-A-North water control unit are shown in Figure 38. There is a general trend that water is removed from the water control unit to the water control catchment, since the Q_{TRANS} value is negative. Based on the definition of Q_{TRANS} being the movement of water from a water control catchment to a water control unit, if the value of Q_{TRANS} is negative, then the net movement of water is from the water control unit to the water control catchment. Comparing the magnitude of the Q_{TRANS} term and the change in storage within the C41-A-North water control unit, the amount of water moving between the catchment and the water control unit is much larger, on average than the amount of storage change solely within the water control unit, Figure 39. The temporal impact of rainfall on Q_{TRANS} is minimal; the release of water from the water control catchment to the water control unit due to a precipitation event is on the order of a day. However, the overall trend from November 1, 2002 to October 31, 2003 is a transfer of water from the water control unit to the water control catchment, Figure 40.

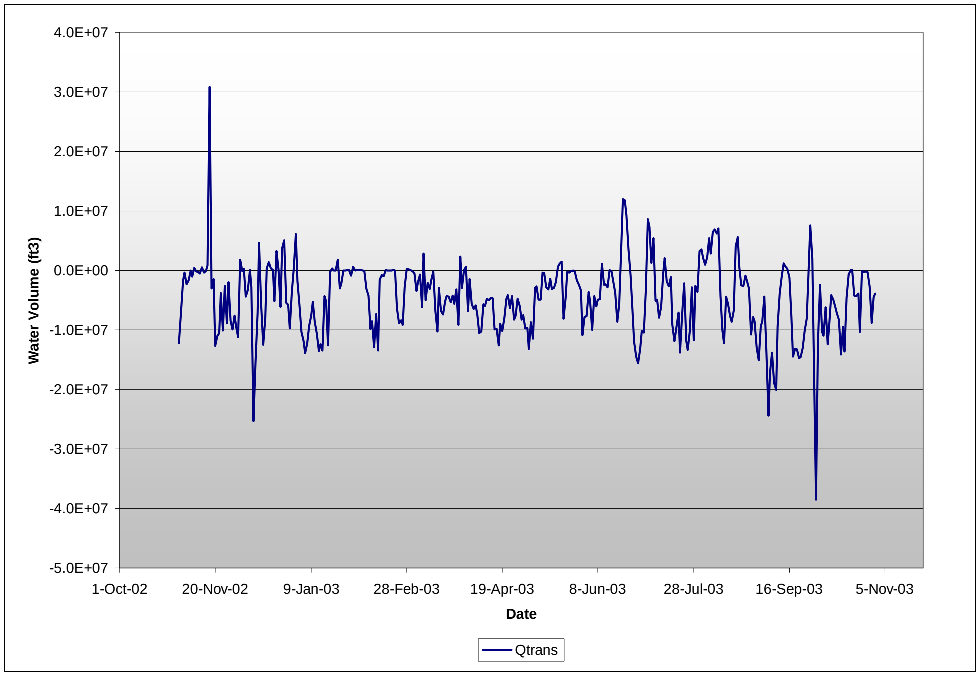


Figure 38 Estimated Qtrans values for C41-A-North water control unit

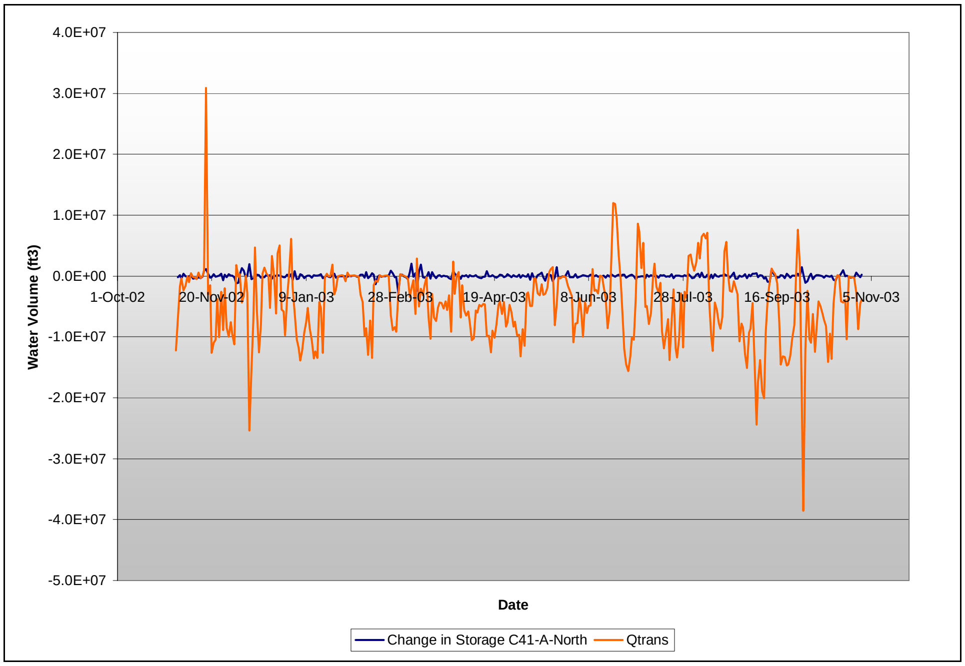


Figure 39 Comparison of change in water control unit storage and Qtrans for C41-A-North

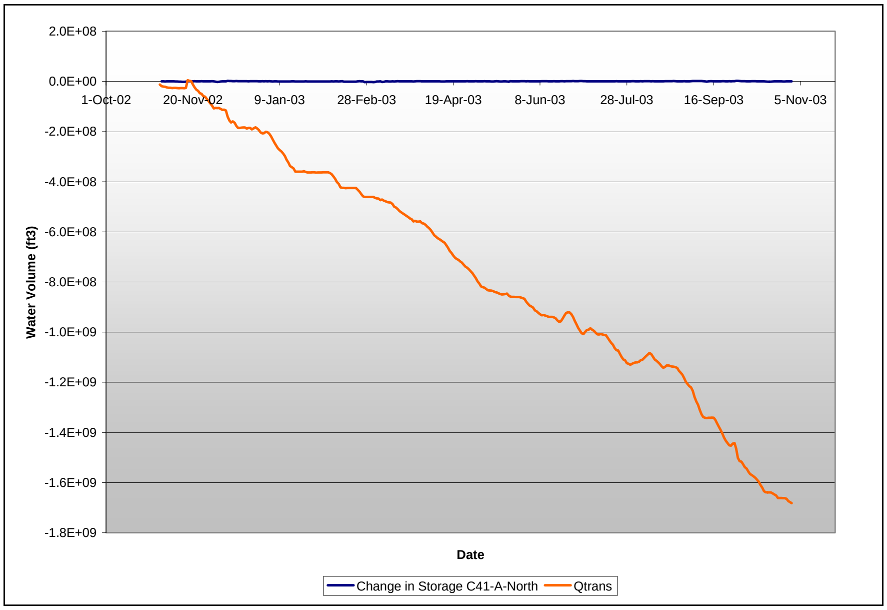


Figure 40 Comparison of Cumulative change in water control unit storage and Qtrans for C41-A-North

The impact of different rainfall estimation techniques on the calculation of Q_{TRANS} for the C41-A-North water control unit is minimal. Three different rainfall estimation techniques, rain gage averaged, NEXRAD, and Rain Areas were tested to determine the impact of rainfall estimations on the calculation of Q_{TRANS}. Regardless of the rainfall estimation technique used to calculate Q_{TRANS} the resulting estimates were within 0.3% of the initial estimation technique, the averaged rain gage value. Although it is important to account for rainfall directly onto the water control unit, deviations between all three rainfall estimation techniques over a year period range from 16.5%, for average rain gage and NEXRAD, to 28.9% for average rain gage and Rain Areas. However, the difference in the cumulative estimates for Q_{TRANS} when using averaged rain gage estimates and Rain Areas rainfall data is only 0.3% over an entire year, Figure 41. Therefore, it is important to include rainfall estimates directly onto the water bodies; however, for smaller water bodies, such as canals, it is as not important what rainfall estimation technique is used.

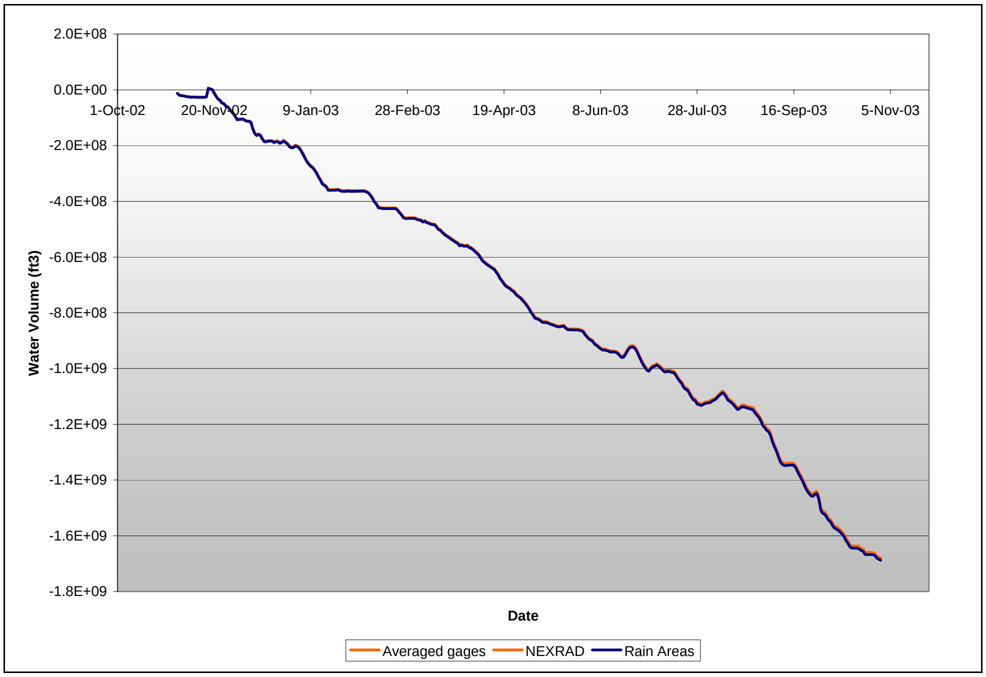


Figure 41 Comparison of Rainfall Estimation Techniques on Qtrans estimate for C41-A-North Water Control Unit

Once the transferred volume of water is calculated then the change in the water balance for the water control catchment can be calculated from the following equation:

$$\Delta S_{C41AN,t} = P_{S82,t} - ET_{\overline{S65CW+S65DXW},t} - Q_{C41AN,t} \qquad \textbf{Equation 42}$$

And the cumulative storage within the water control catchment is calculated based on the equation:

$$S_{C41AN,t} = S_{C41AN,t-\Delta t} + \Delta S_{C41AN,t} \qquad \textbf{Equation 43}$$

The resulting water balance for the C41-A-North canal is shown in Figure 42. For reference and comparison to subsequent analyzes this case is called Case 1.

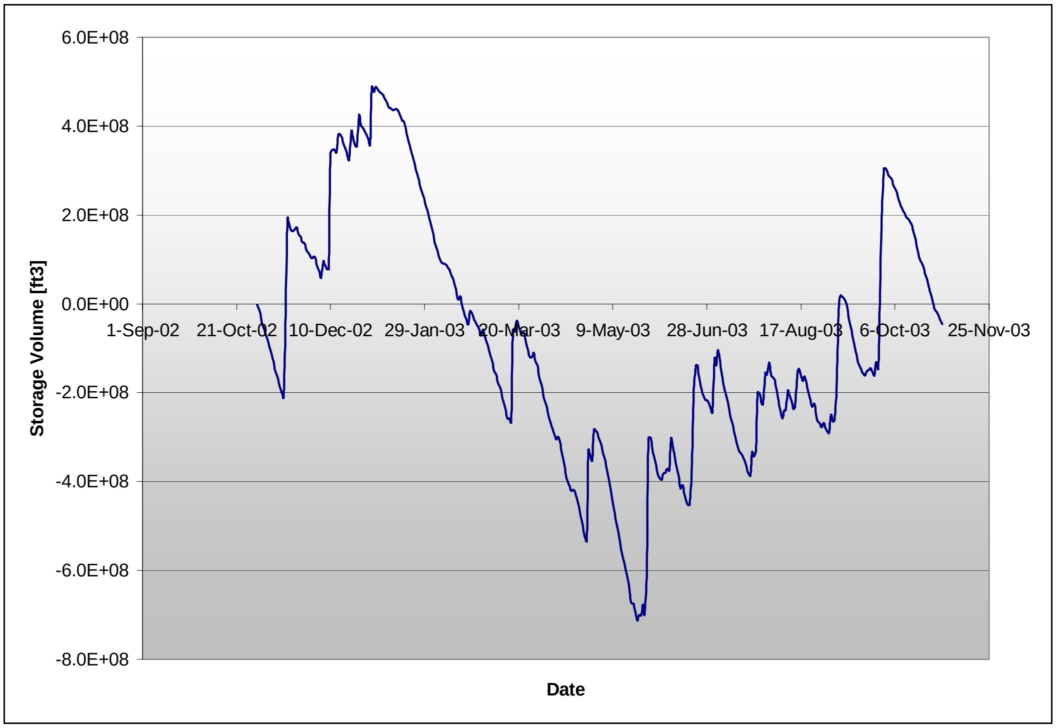


Figure 42 Calculated water balance for C41-A-North water control catchment

Based on the information presented in Figure 42, the amount of water within the C41-A-North water control catchment increases from the start of the time period, November 1, 2002 until mid-January, at which point the amount of water estimated within the water control catchment decreases on average, with slight increases in the amount of water storage with periodic rainfalls. The decreasing amount of water stored in the water control catchment coincides with the dry period of the hydrologic cycle in the SFWMD. The amount of water contained within the water control catchment increases from mid-May until end of the period of record. The average increase in the amount of water contained within the water control catchment coincides with the rainier portion of the water year. The trends represented within this water balance graph are indicative of the general hydrologic cycle observed within the SFWMD. Thus, the information presented in the graph are representative of the conditions which were observed in the SFWMD. Based on the information presented in the graph, it appears that the water year is a typical water year with an average amount of rainfall falling during the year.

It is important to note that the amount of water estimated within the C41-A-North water control catchment is a relative amount of water, the amount of water is compared to the starting of the period of record, November 1, 2002. Thus, if the amount of water stored in the C41-A-North water control catchment is a positive number, then the estimated amount of water within the catchment is greater than the amount of water on November, 1, 2002. Conversely, if the amount of storage estimated in C41-A-North is negative, then the estimated amount of water stored in the catchment is less than the amount on November 1, 2002. This is not an indication of the actually amount of water stored within the water control catchment, but only a relative amount to a given day. A direct estimate of the amount of water stored within the water control catchment will be investigated later.

4.1.1 The importance of Qtrans in the estimation of Water Control Catchment Storage

In the first development of the water balances for the Three Lakes test area, it was assumed that the water balance for the C41-A-North water control catchment could be explained using the vertical water balance for the landscape. It was assumed that the driving forces in the water balance over the landscape are simply due to rainfall and evapotranspiration from the landscape, so there was limited interaction between the water control units and the landscape. However, there are a multitude of water permits issued for the Three Lakes test region for the removal of water from the SFWMD operations system. There are also major releases of water into the canal system, thus it is important to account for this transfer of water between the two components of a water control unit, the water control unit itself and the water control catchment. The importance of accounting for this transfer of water is underscored in Figure 43, which shows the estimated amounts of water contained within the C41-A-North water control catchment accounting for the transfer of water, expressed by the term Q_{TRANS}, and the amount of water estimated without including the transfer of water between the water control unit and the catchment. As shown in Figure 43, if the water transferred between the water control unit and the catchment are not accounted for, then the amount of water estimated within the canal simply using the vertical water balance underestimates the amount of water within the catchment in the summer months and potentially over estimates the amount of water within the catchment in the fall months. However, overall there appears to be little difference between the final estimates of water within the water control catchment between the start of the time period, November 1, 2002 to the end of the time period of analysis, October 31, 2003. Thus, it is important to include in the water balance the transfer of water between the operational canal systems, the water control units and the landscape, the water control catchments.

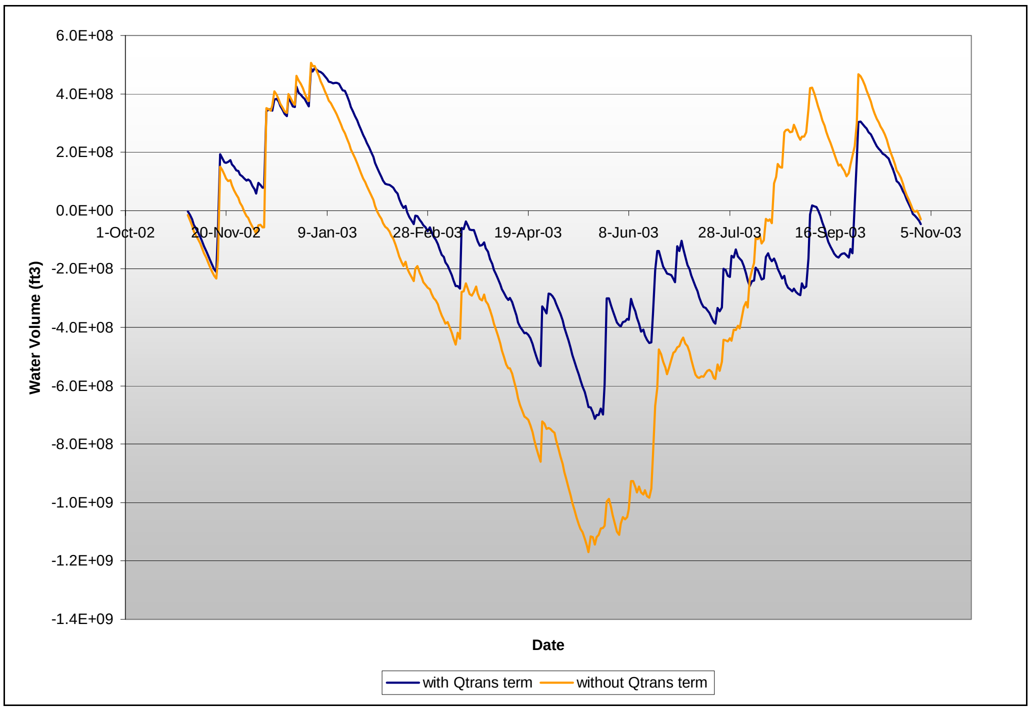


Figure 43 Comparison of Estimated Water Storage in C41-A-North WCC with and without Qtrans term included in water balance calculations

4.2 Estimating water volumes in water control units

As described in Section 4.1, the water volume estimates for the water control unit were based on linear interpolation of the water level between all three stage measurements within the C41-A-North water control unit. Two methods were identified for estimating the canal volumes, the linear method used in the geospatial water balance for the C41-A-North water control unit and a second method, called the Simplified method. The theoretical aspects of the Simplified water volume estimation are explained in Section

3.5.2. The Simplified method is not physically based; however, has been shown to match very closely with the results obtained from more physically based hydraulic models. Both methods require the geometry of the canal to estimate the amount of volume is contained within a canal; however, if a water body that is part of the water control unit cannot be expressed by simple linear geometry, such as a lake, then a different approach to estimate water volumes would be required.

4.2.1 Comparing Linear Interpolation and Simplified Methods

Both methods were used to computer the estimated storage on water within the C41-A-North water control units from November 1, 2002 to October 31, 2003. Both interpolation methods used the stage data gathered from DBHydro for the three structures which define the ends of the C41-A-North water control unit, S68, S82, and S83. Comparing the estimated volumes for each time period for each computation method it was found that the linear estimation method estimates a larger volume of water within the C41-A-North water control unit than the Simplified method, Figure 44. However, the measurement of interest for the calculation of Q_{TRANS} and subsequently the estimation of the amount of water transferred between the landscape and the canals, is dependent on the change in storage, rather than the actual volume estimated within the canal system. Thus the change in storage between the two methods was compared to determine if the two interpolation methods estimated a significantly different volume of water transferred between the canals and the landscape.

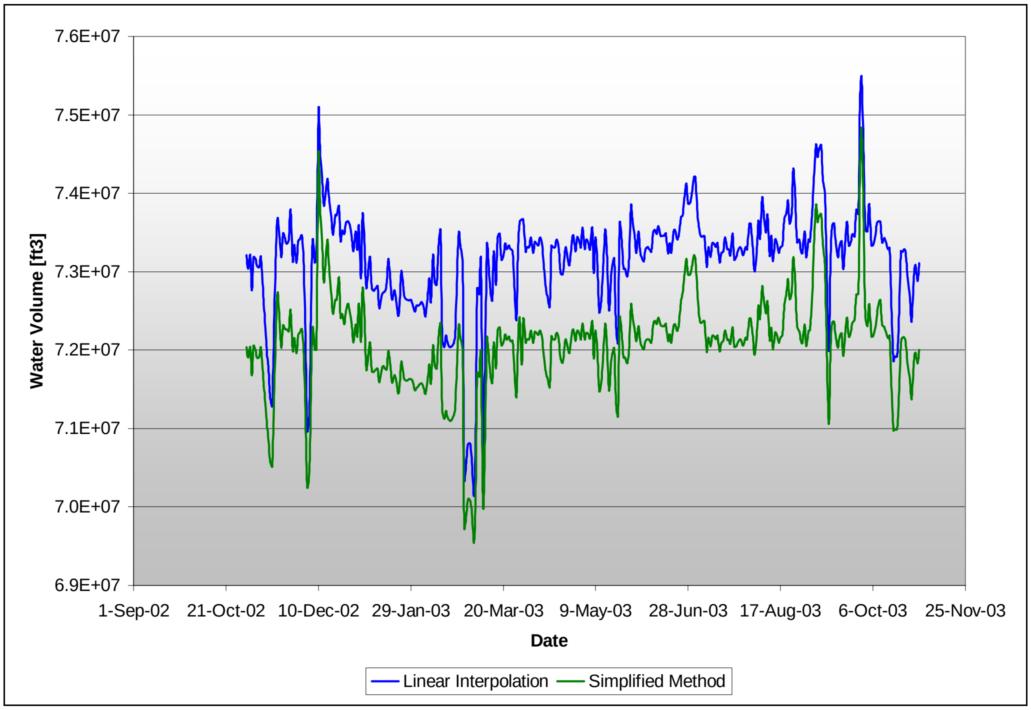


Figure 44 Comparison of Water Volume within C41-A-North by linear interpolation and Simplified Method

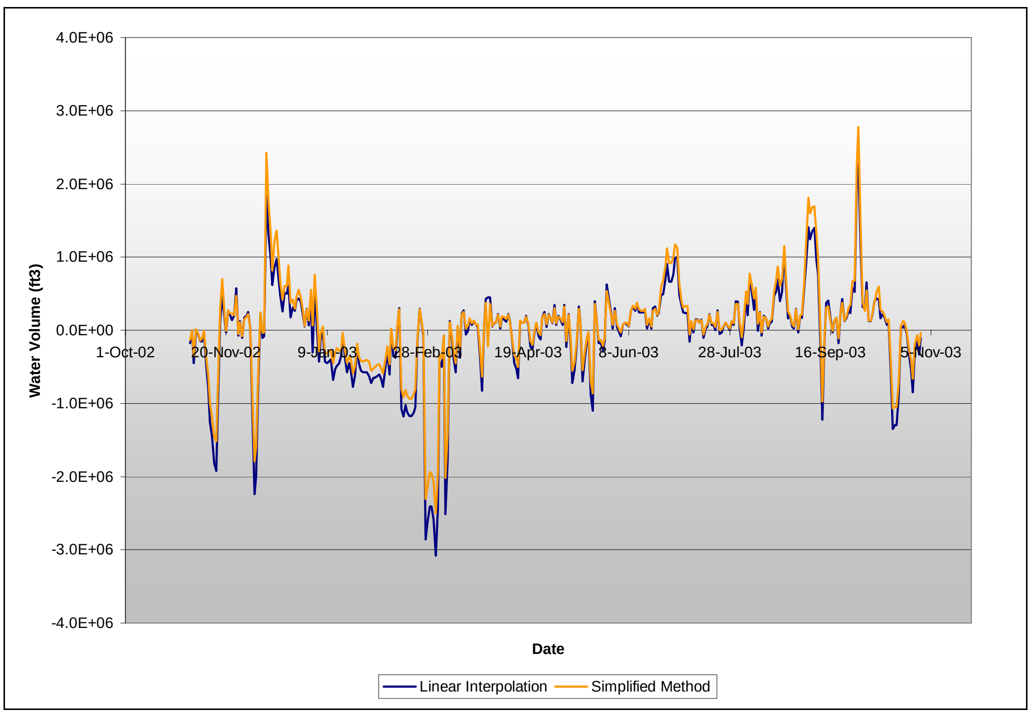


Figure 45 Comparison of Cumulative Volume of Qtrans Estimated using Linear Interpolation Method and Simplified Method

Comparing the change in storage between the two volume estimation methods, the general trend in both estimation methods is similar, Figure 45. The timing of volume increases and decreases are the same, and the magnitudes of the changes are similar. However, to determine if the two produce similar increases and decreases the two volume changes were plotted together on one graph, with the x-axis representing the Simplified method computed values and the y-axis representing the Linear method. If the two methods produce similar changes in storage estimates, then the resulting points should plot along a 1-1 line. However, as shown in Figure 46, there are discrepancies between the two volume estimates, particularly at the extreme ends of the volume changes. In general, all values plot along a similar line, with only one or two stray points falling off the general trend line. When the volume changes in the canal are estimated to be small, both methods produce results estimates that fall on the 1-1 line; however, when the estimates for storage change get larger from one daily time step to the next, then the linear estimation method produces smaller storage change values than the Simplified method does.

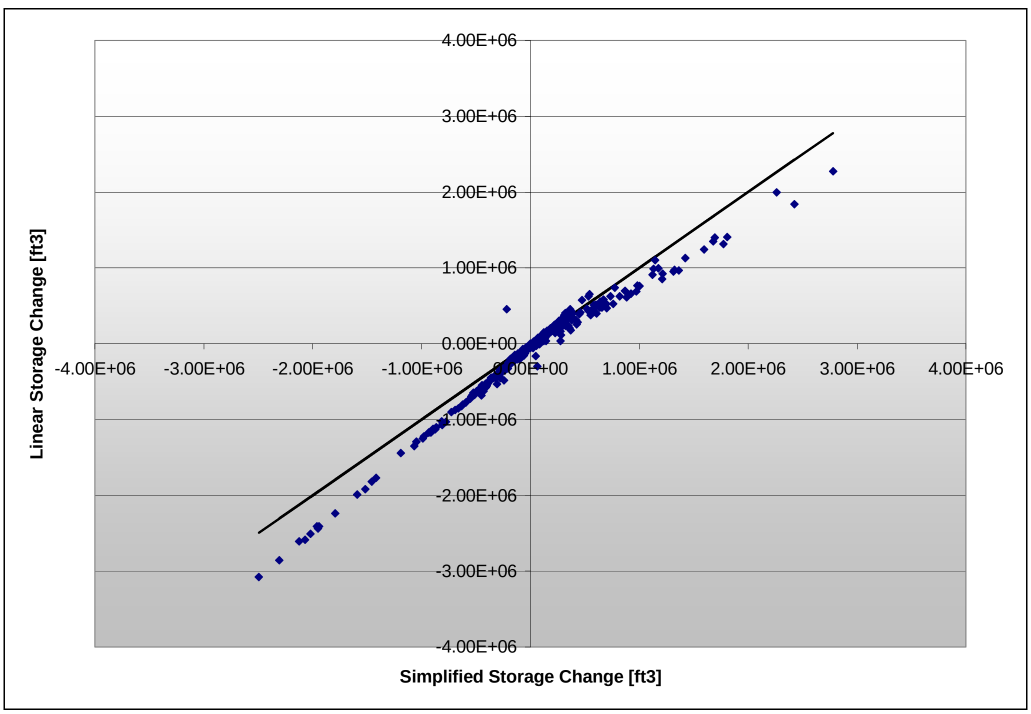


Figure 46 Comparison of Linear and Simplified Methods to estimate change in canal storage

Since the Simplified interpolation method is based on more physically based assumptions the Simplified interpolation method is the recommended interpolation method for the estimation of storage volume within the canal portions of the water control units.

Analyzing the geospatial water balance for the C41-A-North water control catchment, the use of the Simplified method produces little change on the estimated water control catchment storage for the C41-A-North area, Figure 47. Thus, either canal volume estimation method will produce similar results for the overall estimation of water control catchment storage.

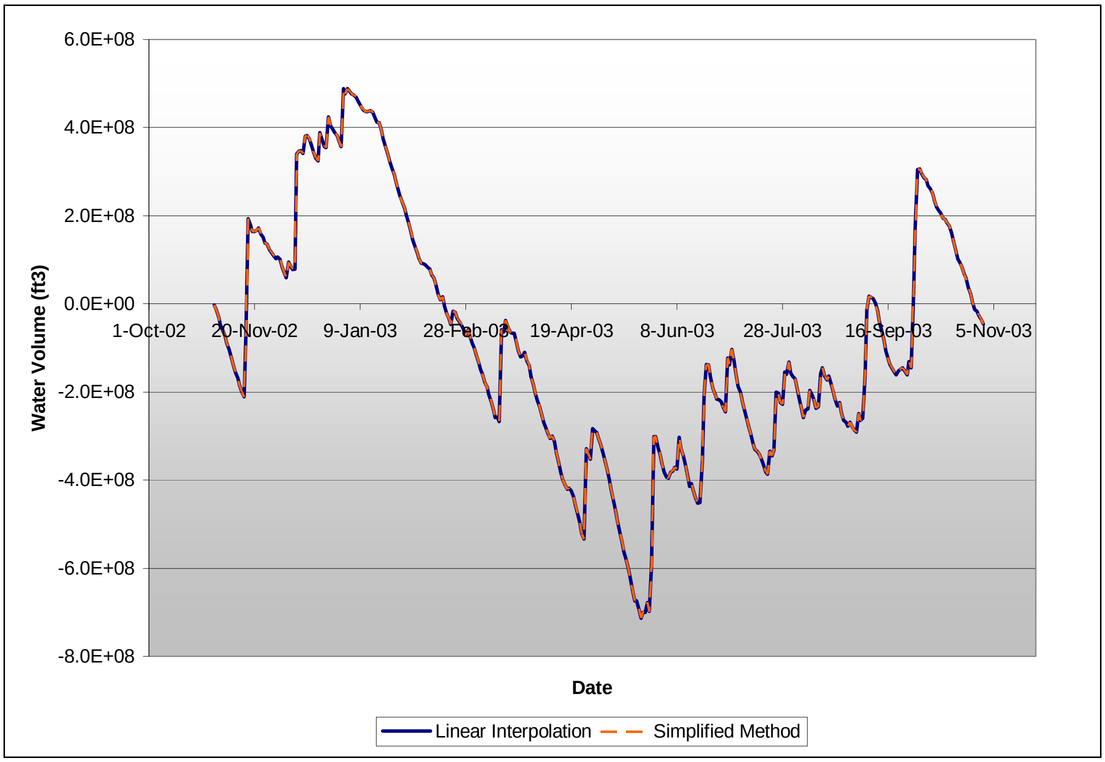


Figure 47 Comparison of Impact of Linear Interpolation and Simplified methods on Water Control Catchment storage

4.2.2 Estimating water volumes in lakes

The linear interpolation and Simplified methods are both appropriate when estimating the volume of water for a trapezoidal or other well defined linear water conveyance structure. However, there are several large lakes within the SFWMD which are not adequately described by linear features. Within the Three Lakes test region there are three lakes of operational significance: Lake Kissimmee, Lake Istokpoga, and Lake Okeechobee. To estimate the volume of water within any lake the bathymetry of the lake is required. The bathymetry for Lake Okeechobee was available through the SFWMD. The bathymetry is based on information gathered from a 1989 survey available for distribution from the SFWMD website in a polygon dataset. The bathymetry information presented to CRWR was in raster form, with a cell size of 668 feet by 668 feet, Figure 48.

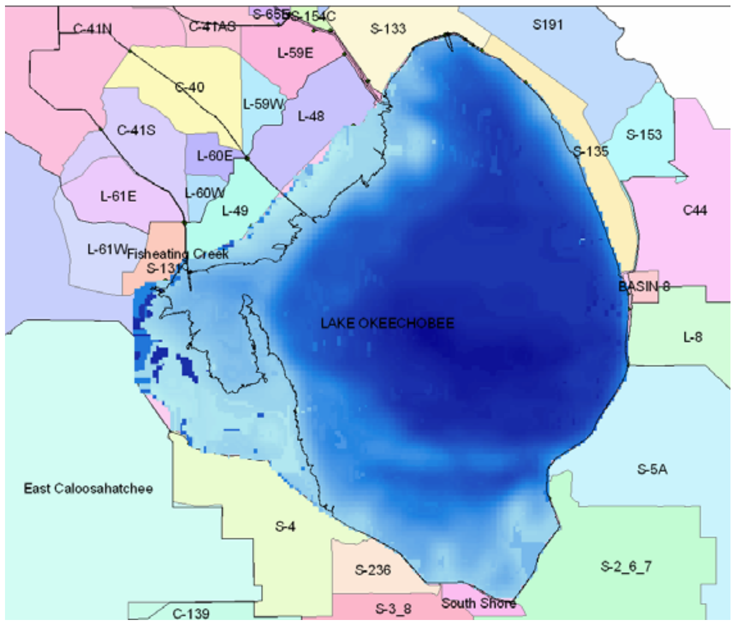


Figure 48 Raster representation of Lake Okeechobee bathymetry

If it is assumed that the bathymetry of the lake of interest, in this case Lake Okechobee is constant in time, then the volume of water contained within the lake can be estimated based solely on the stage measurements recorded on the lake. In the case of Lake Okechobee, the water level recorded at stations around the perimeter of the lake are influenced not only by the volume of water contained within the lake, but the wind direction and local inflows or outflow from the lake. Thus, based on the observations of daily monitors of the lake, the best estimates for the average stage level within the lake are the four stage measurements recorded in the center of the lake, namely, L001, L005, L006, and LZ40. (US ACE, 2005)

4.2.2.1 Estimating a Depth to Storage Curve for Lake Okeechobee

Theoretical water level rasters for Lake Okeechobee were input into GIS. Using the spatial Analyst extension in Arc GIS, the total water volume was calculated using the Raster Catalog tool. The bathymetry raster was subtracted from the theoretical water level, with negative values ignored. Multiplying the sum of the depth rasters by the area of each raster cell produced an estimate for the total volume of water. The resulting depth curve can be broken into two portions. Lake Okeechobee is surrounded by a large dyke, which holds rising waters away from the surrounding communities of Lake Okeechobee. Thus, the first portion of the depth curve is before the observed water level reaches the dykes that surround the lake, once the water reaches the dykes, the volume of water increases linearly with an increase in water level. Therefore, the depth curve presented in Figure 49 is valid for observed water levels below 14.4 feet above sea level. Above 14.4 feet above sea level, the water volume in the lake is estimated to rise linearly. Lake Okeechobee increases by 442,403 acre-ft per foot increase in the observed water level above 14.4 feet, based on an estimated area of Lake Okeechobee of 583 square miles, or 1.628×10^{10} ft^2. Based on the bathymetry data, a reasonable water volume estimate can be made using the average observed water level.

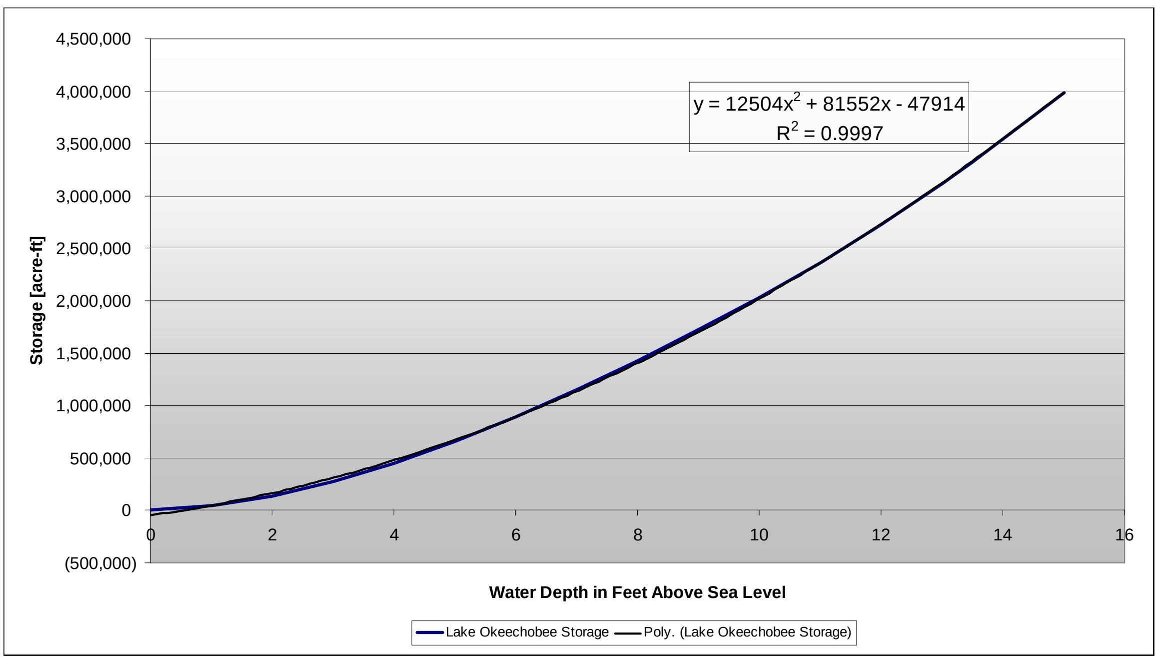


Figure 49 Depth to Storage Curve for Lake Okeechobee, valid for water levels less than 14.4 feet above sea level.

Bathymetry data is required for any water body feature that cannot be estimated using linear canal geometry.

4.3 Estimating areal precipitation rates

In the geospatial water balances was analyzed in Section 4.1 for the C41-A-North water control unit, the precipitation estimate for the analysis period used the rainfall amounts observed at rain gage station at structure S82, identified by the DBKey 16655. The S82 rainfall gage is part of the OMD rainfall gage network. There are 69 OMD rainfall gages which are monitored regularly by water managers and operators at the SFWMD that have rainfall information associated with them in DBHydro as well as a documented spatial location within the SFMWD. The majority of the OMD rain gages are located around Lake Okeechobee, the agricultural regions south of Lake Okeechobee and in the Miami-Dade region. There are a few OMD rain gages in less populated areas, such as the Everglades National Park. Twenty-five OMD rain gages are contained within one mile of the Three Lakes test region, Figure 50.

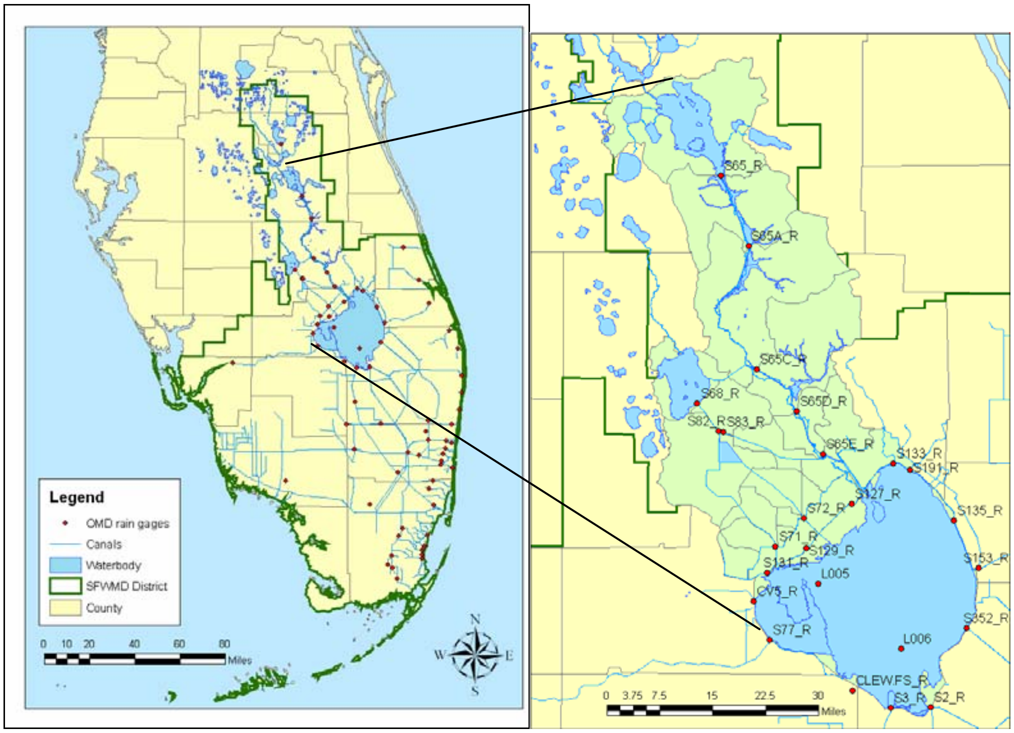


Figure 50 OMD rain gages for SFMWD and detailed view of Three Lakes test area

Since the OMD rain gages are currently being used by water managers and operators of the SFWMD, these gages provide a basis for estimation of areal precipitation rates. Within the C41-A-North water control catchment there are three OMD rain gages, S68_R, S82_R, and S83_R identified by DBKey identifiers 16654, 19655, and 16656. The rainfall information recorded at station S82_R has previously been used in the water balance analysis. Comparing the rainfall total between the three rain gages in the water control catchment, the two rain gage stations at the southern end of the C41-A-North water control catchment recorded similar rainfall amounts, where as the rain gage located near structure S68 recorded a larger cumulative rainfall. The largest discrepancy between the northern and southern portions occurs during the second half of the time period, from May to October of 2003. The recorded rainfall for each gage is summarized in Table 6.

Table 6 Measured Rainfall at the three OMD rain gages located within C41-A-North WCC

Rain Gage	Cumulative Rainfall Amount [in]
S68_R	46.14
S82_R	39.25
S83_R	39.27
Average	41.64

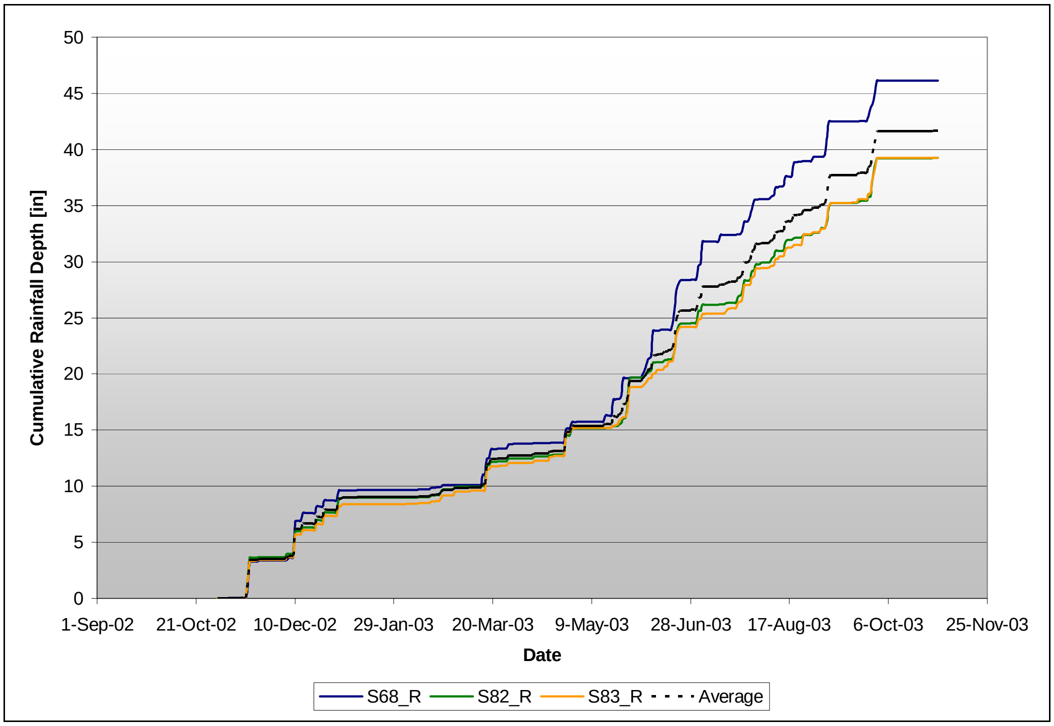


Figure 51 Comparison of cumulative rainfall measurements recorded at OMD stations S68_R, S82_R, S83_R, and arithmetic average.

4.3.1 Arithmetic Average Precipitation

All three measurements are representative of the areal precipitation that fell in the C41-A-North water control catchment. Based on a review of rainfall estimation techniques, arithmetic average techniques are common practice for estimating the rainfall within a single watershed or basin of interest when more than one rain gage exists in the basin. The arithmetic average of the three gages, the fourth line in Figure 51 is computed based on the daily average rainfall and then sums the daily average rainfall to calculate the cumulative rainfall for C41-A-North.

$$\overline{R}_{C41AN} = \sum_{t} \frac{1}{3}(R_{S68\_R} + R_{S82\_R} - R_{S83\_R}) \qquad \textbf{Equation 44}$$

If the average rainfall is used as a vertical input flux to the geospatial water balance then the estimated rainfall that falls within the C41-A-North water control catchment is estimated to be 41.64 inches per year, a slightly larger total rainfall than the areal estimated rainfall if only the S82_R rain gages is used. The resulting water balance over the C41-A-North water control catchment, Figure 52, shows deviation from the original water balance in the second portion of the water year, starting around May of 2003.

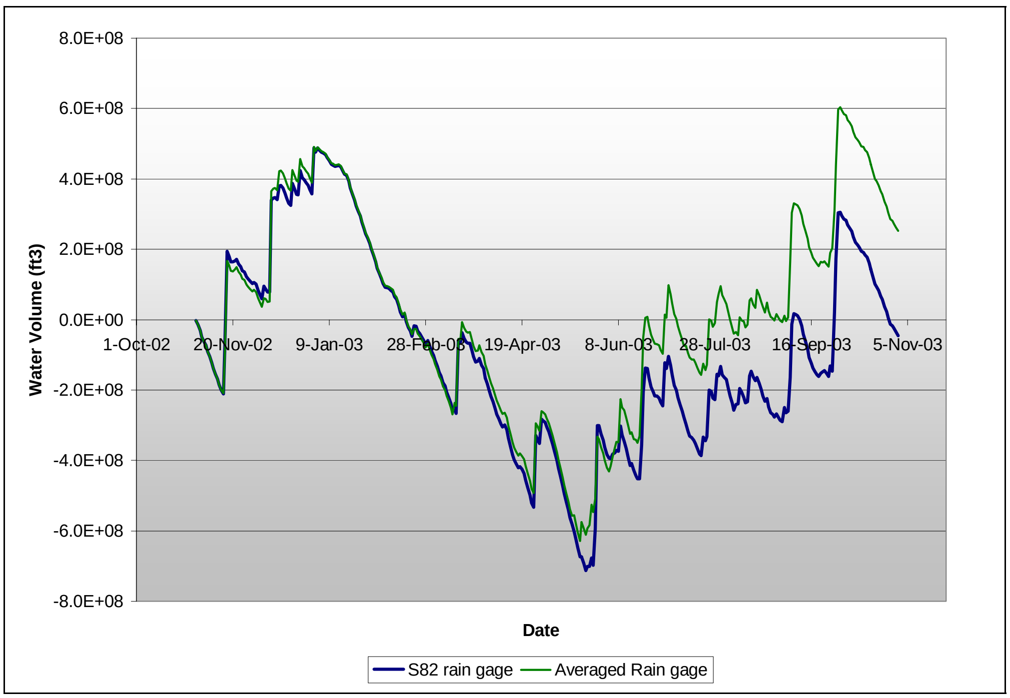


Figure 52 Geospatial water balance over C41-A-North catchment using two rainfall estimation methods: single rain gage at S82 and arithmetic average of three rain gages

4.3.2 Thiessen polygon precipitation

To estimate the areal precipitation rate using Thiessen polygons for the OMD network need to be created the Thiessen polygons had to be created. There are several tools freely available via the ESRI arcscripts website that provide Arc GIS tools to create a Thiessen polygon network. Using the 69 OMD gages that exist in the SFWMD, Thiessen polygons were created, Figure 53. There is generally poor coverage of the western and southern portions of the SFWMD, due to lower density of rainfall gages compared to the areas along the eastern coast and around Lake Okeechobee. If the OMD rain gages are used to approximate the rainfall in each water control catchment that surrounds the OMD rain gages, then in most cases the OMD rain gages are appropriate to estimate areal rainfall estimates. However, it is still not proven that a single rain gage is appropriate for estimating the areal rainfall for each water control catchment.

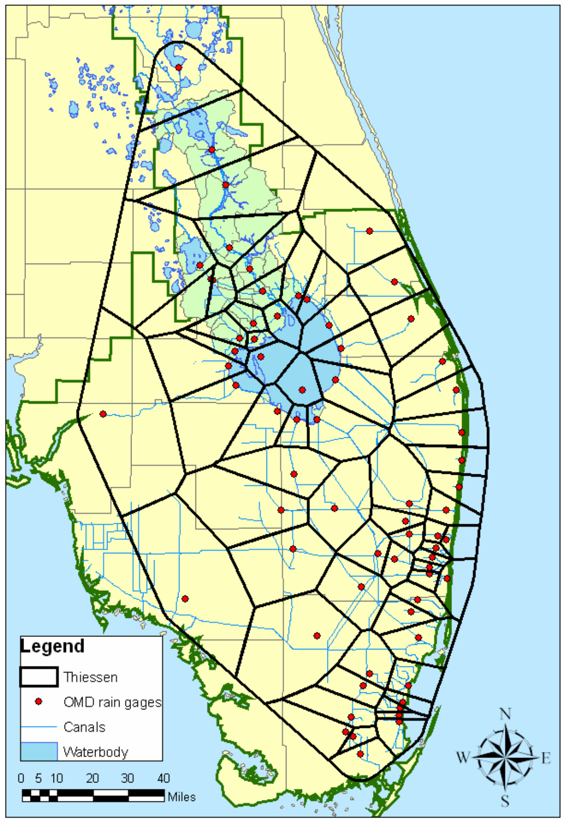


Figure 53 Thiessen polygon network created using OMD rain gages

There are five OMD rain gages that are associated with the C41-A-North water control unit and catchment: S68, S82, S83, S65C, and S65D gages. Each rain gage contributes a percentage of the total rainfall to the entire C41-A-North water control catchment. At this point, it is difficult to determine the contributing amount of rainfall for each water control unit. Thus, for this rainfall assessment it was assumed that the rainfall calculated for the water control catchment was appropriate to estimate the rainfall over the water control unit. Each gage is given a weighting factor to calculate the estimated areal rainfall rate for the C41-A-North area. If any gages are not operational, then the Thiessen polygon network is recreated, using only the rain gages that are functioning at the time. During the time period of interest there are two occasions when the S68 rain gage did not have a reported rainfall amount, thus the Thiessen polygon network was re-run without including the s68 rain gage, the weighting factors for the C41-A-North water control catchment are increased for each operating rain gage.

Table 7 Summary of Thiessen polygon weighting factors for C41-A-North water control unit

	Weighting Factor [%]	**Weighting Factor [%]**
	All OMD rain gages	Without S68 gage
S65C_R	14.9%	21.3%
S65D_R	14.4%	15.2%
S68_R	51.6%	-
S82_R	13.2%	57.1%
S83_R	5.9%	6.3%
Total	100.0%	100.0%

The estimated rainfall for the C41-A-North water control unit using the Thiessen polygon method is 46.74 inches per year, which is a 12.2% increase in the total amount of rain estimated, comparing the rainfall estimate to the areal estimation using the average of the three gages that fall within the C41-A-North water control catchment. This increase is associated with two factors. First, an increase in the contribution of S68 rain fall gage to the estimate of the areal average, which accounts for over 50 percent of the total rainfall, second the inclusion of the two S65 rain gages. The S65 gages recorded higher yearly rainfall values, 48.69 and 55.79 inches per year respectively, for November 1, 2002 to October 31, 2003 than the rain gages within the C41-A-North water control catchment.

The increase in rainfall estimates using the OMD rainfall gages increases the amount of water estimated to be contained within the C41-A-North catchment, compared to the Case 1 water balance using the same water balance estimating technique. There is a particular increase in the volume of water estimated towards the latter part of the period of interest, from May onwards.

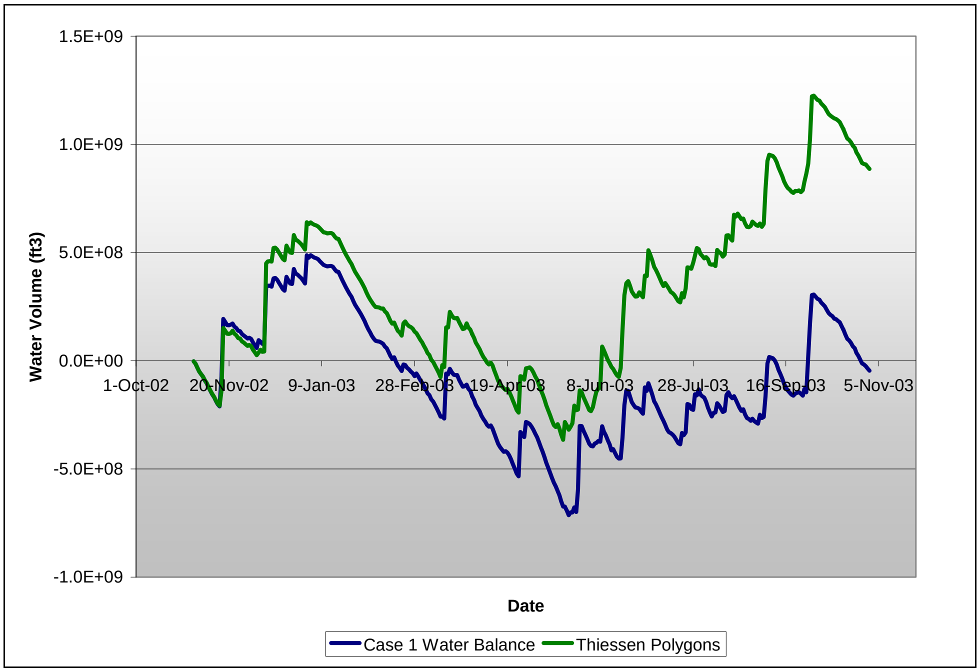


Figure 54 Comparison of Thiessen polygon rainfall and S82 rain gage rainfall impact on water balance

4.3.3 NEXRAD precipitation estimates

The NEXRAD rainfall cells over the Three Lakes test region are approximately 2 km by 2 km grids. The data provided to CRWR was quality-controlled daily rainfall data for each pixel, for more than 33,000 pixels that cover the SFWMD. To estimate the areal rainfall for the C41-A-North water control catchment, the time series information must be converted from point time series information, or attribute information, to a polygon, to a raster and then to a feature time series for each water control catchment. Based on the temporal and spatial processing described in Section 3.2.2, NEXRAD rainfall estimates for all of the water control catchments were calculated using three different raster cell sizes. However, the computation time for the raster cell sizes depended heavily on the size of the raster cells size being used, Table 8. As the cell size increases the total number of cells that the processing program must create in order to estimate the areal precipitation rates.

Table 8 Computation time required to create areal rainfall estimates from NEXRAD grids

Grid Size	Grids to Compute	Total Computation Time [sec]	Raster Computation Time [sec]
500m	7,648	11,358	7,877
250m	30,592	19,246	8,531
100m	764,800	-*	10,303

* computations for 100m grid could not be processed in its entirety, therefore no estimate of total computation time is available.

The temporal and spatial analysis required to create the historic areal average rainfall estimates for the Three Lakes test area for a one-year period took a minimum of 190 minutes. There were 365 daily time steps within the time period of analysis for the historic rainfall data, if 15-minute interval data were used to estimate daily rainfall data, then within a single day of NEXRAD data there would be 96 time steps per day. Thus, the processing time required to estimate a daily total, based on 15 minute NEXRAD data, for the Three Lakes test area would be 50 minutes. The processing time required to compute areal rainfall averages would increase with an increase in the total number of NEXRAD cells used. Thus, increasing the overall area of analysis from the Three Lakes region to the entire SFWMD would potentially increase the processing time by a multiple of 17. Assuming the processing time increases linearly with an increase in the number of NEXRAD cells.

Comparing the results of the areal rainfall estimates using the NEXRAD grids as the basis, the rainfall estimates for the C41-A-North water control catchment are consistently lower then the rainfall estimates obtained using the three of the previous estimation methods: single gage, gage average, and Thiessen polygons, Figure 55. This observation is consistent with previous studies which have shown NEXRAD rainfall estimates are generally lower than other estimation techniques. However, upon further comparison of the rainfall values, the largest observed difference between the two data sets occurs on a single day, November 17th, 2002. The precipitation recorded at the S82 rain gages site on that day was 2.46 inches and the calculated precipitation over the same time period using NEXRAD data was 0.65 inches. The impact of this single discrepancy between the two measurement types significantly skews the graph of the water balance. If it is assumed that both rainfall estimation techniques measure the same rainfall on that day and the cumulative rainfall is re-plotted in Figure 56, then it becomes apparent that the gage estimation techniques and the NEXRAD estimation techniques show the same trend in the amount of rainfall estimated over the C1-A-North water control catchment.

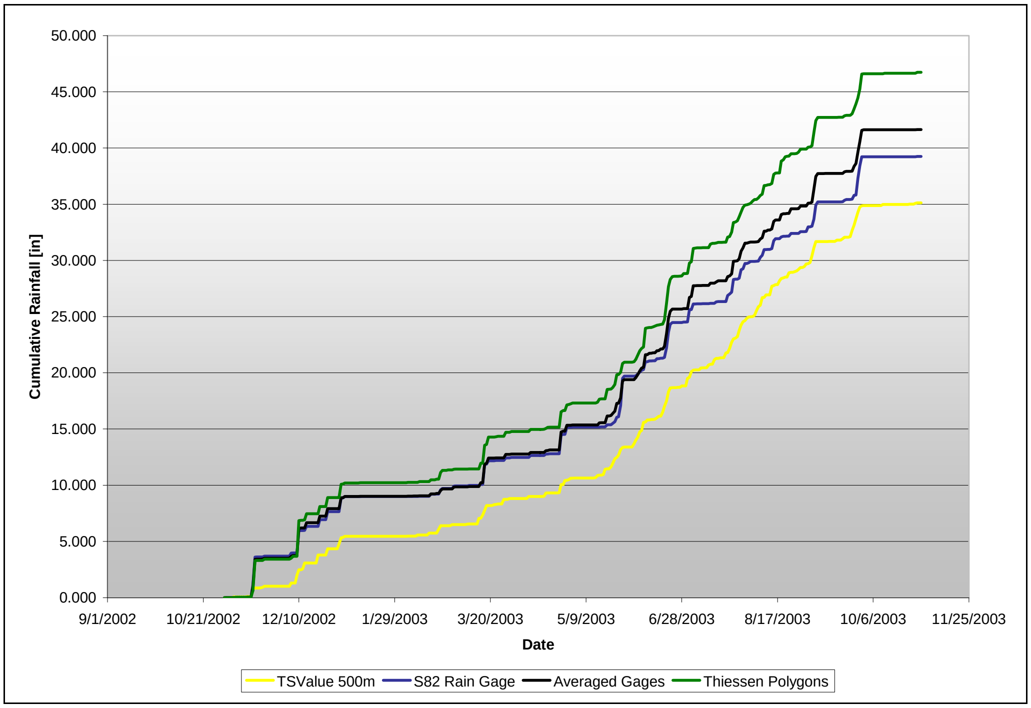


Figure 55 Comparison of NEXRAD rainfall estimates to other estimation techniques for C41-A-North water control catchment

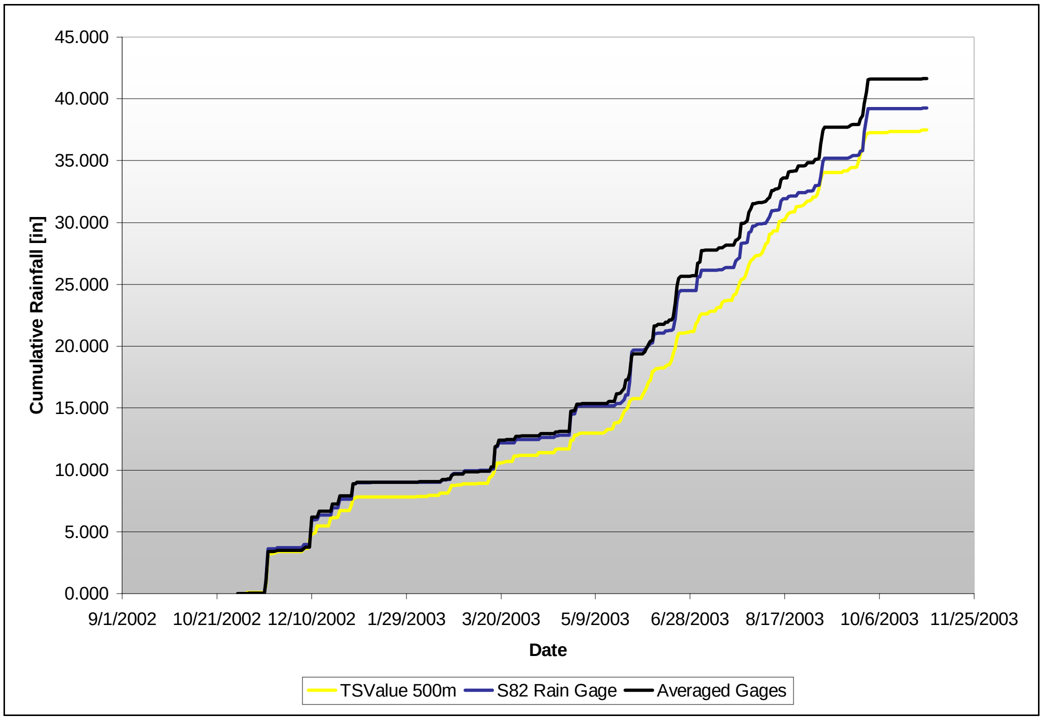


Figure 56 Comparison of adjusted NEXRAD rainfall with S82 rain gage and average areal rainfall estimation for the C41-A-North water control catchment.

The difference between the three raster cell sizes was minimal when estimating rainfall in all of the water control catchments within the Three Lakes test area. Within the C41-A-North water control catchment the estimate for cumulative rainfall within the catchment was 34.30 inches, 35.16 inches, and 35.13 inches for the 100 m, 250 m, and 500 m grids, respectively. There is no significant difference between the rainfall estimates obtained using the 250 m grid and the 500 m grid. Plotting the cumulative rainfall over the C41-A-North water control catchment, the two lines fall almost directly onto of each other, Figure 57.

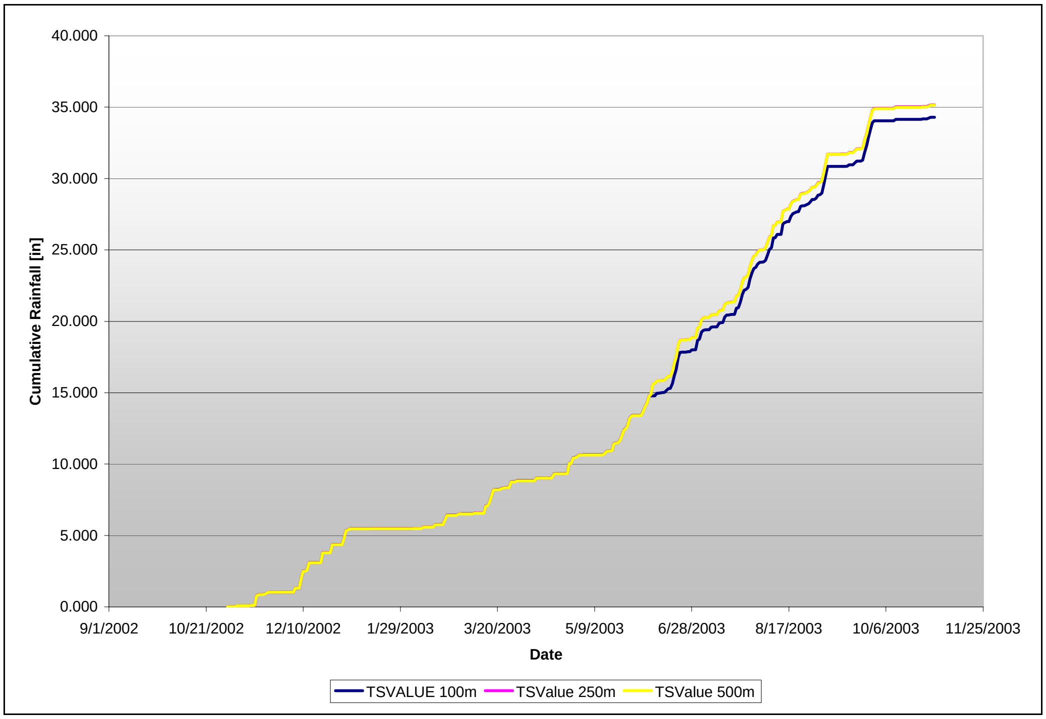


Figure 57 Comparison of NEXRAD cell size on cumulative rainfall estimates for the C41-A-North water control catchment

As would be expected with a decrease in the cumulative rainfall estimate, the geospatial water balance over the C41-A-North water control catchment over the entire time period of interest shows a general decrease in the relative amount of water stored in the catchment, Figure 58. The impact of each grid cell size on the overall water balance for the C41-A-North canal is minimal, and the trend is consistent with the water balance presented for the 500m grid cell size. However, the trend of the water balance for both rainfall estimation methods is the same.

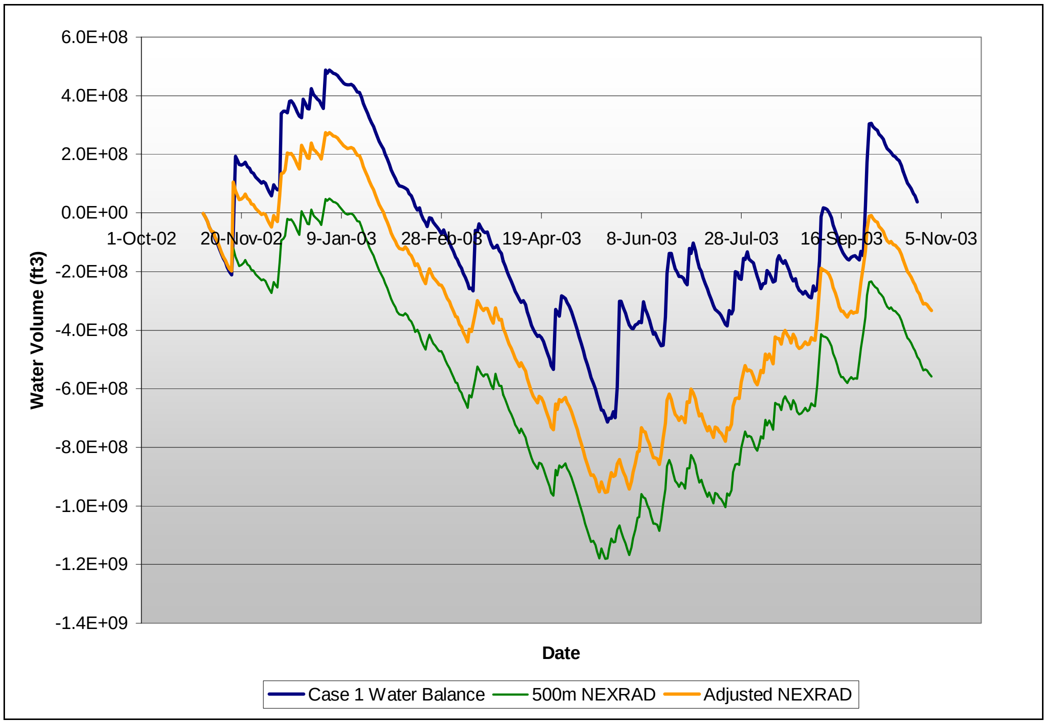


Figure 58 Impact of NEXRAD cells on geospatial water balance over the C41-A-North water control catchment

The benefit of the NEXRAD cells, compared to the other methods described so far is the continuous spatial and temporal coverage. With point measurement data, there are areas with the SFWMD that do not contain a significant number of rainfall gages, thus the use of rainfall estimation techniques using point gage data is not conducive to areal estimations of rainfall over a desired area. The NEXRAD precipitation estimation has the added benefit of real-time results and predictive rainfall rates, for the near-term, on the order of several hours. The near-term rainfall forecasting information provides added benefits to water managers within the SFWMD when trying to predict the spatial variability of rainfall over the SFWMD.

4.3.4 Rainfall Rain Area Precipitation Estimates

The final potential rainfall input for the geospatial water balance for the SFWMD is the use of rain area precipitation estimates. There are fourteen rain areas within the SFWMD which are considered operationally similar for OMD operations. The rainfall information gathered by the SFMWD and provided to CRWR for these regions includes rainfall data for the time period of analysis, November 1, 2002 to October 31, 2003. Based on the results presented for other areal estimation techniques, there is significant spatial variability of rainfall. There are 25 OMD rain gages: with the majority of the gages within close proximity to Lake Okeechobee, however, there are only three rainfall rain areas, Figure 59. The three rainfall values recorded for each rain area are significantly less variable than the rain gages or NEXRAD cells. The spatial variability of rainfall within the 24 water control catchments in the Three Lakes test area is decreased by a factor of 8 if the rain area information is used. The rain area estimates are derived from point measurements recorded in and around the SFMWD. The point measurements include, but are not limited to, the OMD rain gages within the SFWMD. The benefit to the use of the rain areas is that SFMWD meteorologists issue forecasts for the amount of rainfall predicted across a rainfall area for a 24 hour period.

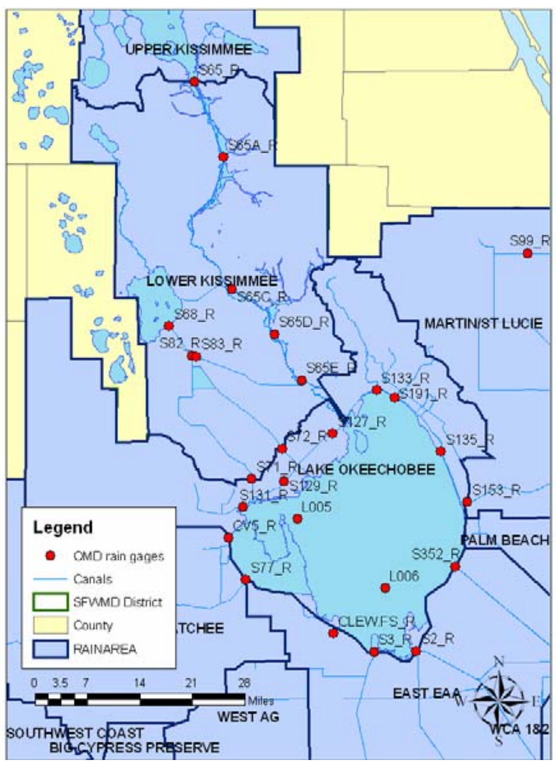


Figure 59 Rainfall rain areas and OMD gages within the Three Lakes test area

Twenty-four rain gages are used to calculate the rain area rainfall amount for the Lower Kissimmee rain area, which includes the C41-A-North water control catchment. These gages include the OMD gages contained within the C41-A-North water control catchment: S68_R, S82_R, and S83_R. However, the cumulative rainfall estimate for the Lower Kissimmee rain area is 52.98 inches of rain over the time period of analysis. This is a difference of well over 10 inches of rain compared to all other rainfall estimation methods. A 10 inch difference over a year period can significant change in the estimate of the amount of water stored within a water control catchment. For the C41-A-North water control catchment the use of the Lower Kissimmee rainfall rain area estimate for areal precipitation produces a water balance with a significant amount of water stored on the landscape, Figure 60. As with previous water balance comparisons, the increased total precipitation estimated using the rainfall rain area method increases the estimated water storage on the C41-A-North water control catchment over the time period of interest, with a significant deviation from the Case 1 water balance in the second portion of the time period, from May to November.

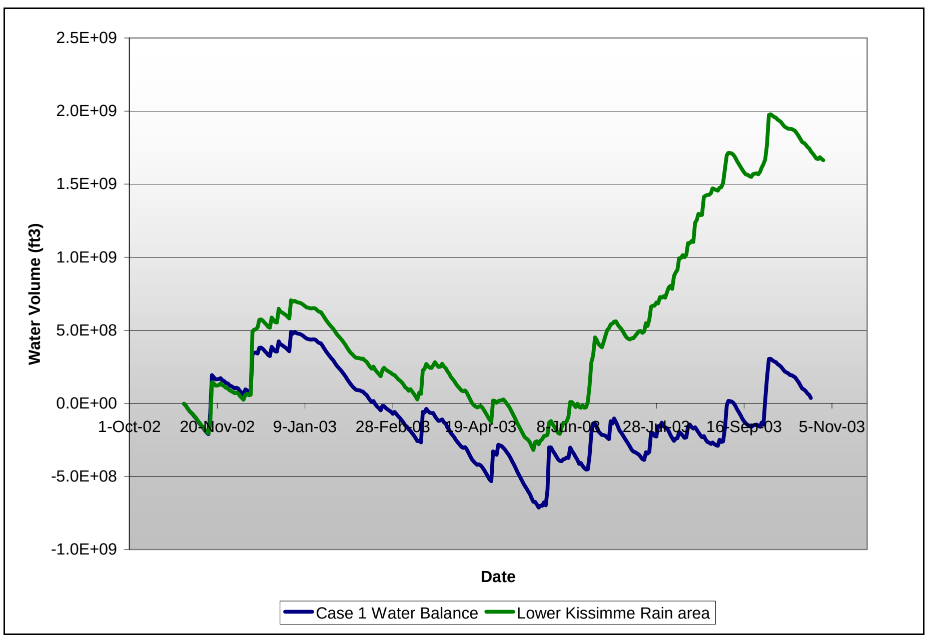


Figure 60 Comparison of Lower Kissimmee Rain Area rainfall estimate to geospatial water balance method

4.3.5 Comparison of Areal Estimation Techniques

This deviation after May of 2003 was observed in all of the rainfall estimation techniques compared to the Case 1 water balance. Plotting all previous rainfall areal estimation techniques for the C41-A-North water control catchment together it is apparent that there are significant temporal differences between them, Figure 61. In particular, there is greater discrepancy between the rainfall values in the second half of the time period of analysis. This is potentially due to the nature of rainfall during the summer months in Southern Florida. In the summer months the causes of summer precipitation are due to tropical sea breezes and introduction of energy due to solar radiation. This produces rainfall that is more spatially variable than winter rainfall, which is primarily dominated by frontal movements.

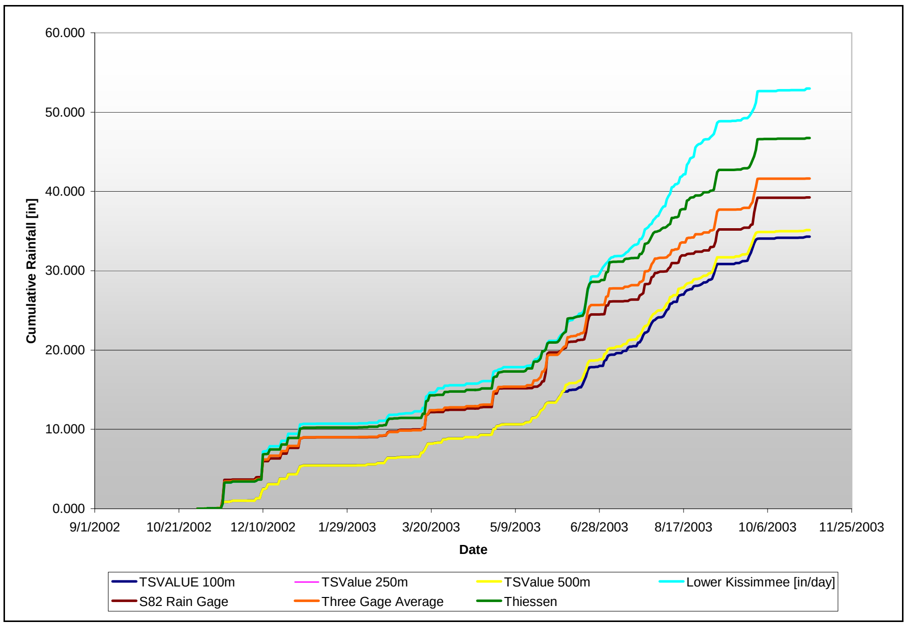


Figure 61 Comparison of areal rainfall estimates for the C41-A-North water control catchment

Based on the estimates of areal rainfall over the C41-A-North water control catchment, the use of NEXRAD data should produce a storage estimate lower than the other estimation techniques available; however, the use of NEXRAD data captures the spatial variability of rainfall that is not captured with the rainfall rain area data. One of the goals of the SFWMD is to create a water balancing program that will predict the storage capabilities and requirements of the water control catchments within the SFWMD on a real-time or near-real time basis. If the requirement is solely to provide a real-time basis of information then any of the areal estimation techniques described could be used in the geospatial water balance method. However, if the ultimate goal is the provide water managers with a near-real time estimate of the amount of water stored within a water control catchment, then it is preferable to use a data set that will provide the water managers with a near-real time estimate of predicted rainfall. As shown in Table 9, only the rainfall rain areas and NEXRAD data provide near-real time estimates for rainfall. The largest difference between the two methods of estimating rainfall amounts is the assumption of spatial variability. One of the main assumptions when delineating the OMD rainfall rain areas was the assumption that on a daily basis there is minimal difference between in rainfall between the regions in the SFWMD. Even on a daily time step there are significant differences in the estimated amount of areal precipitation within a water control catchment. Due to the large area covered by a single water control unit, the C41-A-North water control unit covers an area of 34,277 acres, and the potential for highly variable rainfall, particularly in the summer months, the assumption that rainfall on a daily basis within a single rainfall rain area is equal does not appear to be adequate.

Table 9 Summary of Areal Estimation Techniques

Rainfall	**Readily Available**	**Spatially Variable?**	**Continuous?**	**Near-term forecasts Available?**
OMD Rain Gages	Yes	Yes	No	No
Rainfall Rain Areas	Yes	Limited	No	Yes
NEXRAD	Yes	Yes	Yes	Yes

Based on the NEXRAD data sets spatial variability of rainfall over a daily time step for each water control unit and water control catchment, as well as the availability of near-term forecasts it is recommended that NEXRAD data be used as the precipitation input to the geospatial water balance method.

4.4 Estimating Evaporation and Evapotranspiration rates

Within the geospatial water balance calculations there are two potential types of water movement out of the control volume, evaporation and evapotranspiration. There are two methods to produce a time series of information regarding evaporation and potential evapotranspiration: measured data and modeled data. In the current analysis of the geospatial water balance, it is assumed that the evaporation from free water bodies can be approximated from the potential evapotranspiration rates recorded throughout the SFWMD. There are 20 recording sites within the SFWMD for potential evapotranspiration, of which 16 recording sites contain current potential evapotranspiration information. Additionally, there are 15 pan evaporation sites within the SFWMD. Both types of recordings are direct measurements of the evaporation and potential evapotranspiration from free surface water bodies and landscapes. The actual rate of evapotranspiration from the land surface is dependent on the vegetation type and the meteorological conditions at the site. Therefore, the use of one measurement to estimate the areal evapotranspiration rate from a single water control catchment may not be appropriate. The development of continuous estimates of evapotranspiration in space and time may be appropriate. This analysis is where the use of models to extrapolate the information would be required. Such long-term average information was shown in Figure 6, without additional information these long-term averages are an excellent first attempt to estimate the evapotranspiration from the landscape or a free water surface.

4.4.1 Measured Potential Evapotranspiration

There are 20 potential evapotranspiration sites within the SFWMD that record the potential evapotranspiration from a site on a daily basis. Comparing the results of the two closest potential evapotranspiration measurement sites to the C41-A-North water control catchment the S65CW and the S65DW the cumulative potential evapotranspiration for the two sites was 1339.1 and 1330.1 mm per year, or 52.72 and 52.37 inches of water per year, respectively. However, there is a week's worth of data missing from weather station C; in order to estimate the total amount of potential evapotranspiration over the entire year, the values recorded at weather station S65DW were substituted for the missing data. This processing increased the estimated potential evapotranspiration to 1371 mm per year, or 53.98 inches. Since neither gage falls within the C41-A-North water control unit, the average measurements recorded at both weather stations was used to estimate the potential evapotranspiration for the C41-A-North water control unit. These numbers are approximately the same as the average amount of rainfall that falls on the region in a given year, approximately 1350 mm per year, or 53.15 inches per year. It is assumed that due to the quantity of ponded water within the Three Lakes region, covering nearly 30% of the total land surface within the C41-A-north water control catchment, and the small depth the water table, that the evapotranspiration rate from the landscape is approximately equivalent to the measurement potential evapotranspiration rate. The measurements for potential evapotranspiration are reported on a daily basis. Therefore, the use of real-time data may not be appropriate; however, the rate of potential evapotranspiration is correlated with incoming solar radiation and maximum day time temperatures (Abtew, 2001). Solar radiation and maximum daily temperatures are cyclical through the year, Figure 62; therefore, in absence of additional potential evapotranspiration data for a daily time step the long term average of a given day would be an appropriate estimate. Therefore, if a daily estimate, or smaller time step, of evapotranspiration is required, then the use of long-term average potential evapotranspiration measurements would be appropriate, with an adjustment at the end of the day to account for the measured potential evapotranspiration.

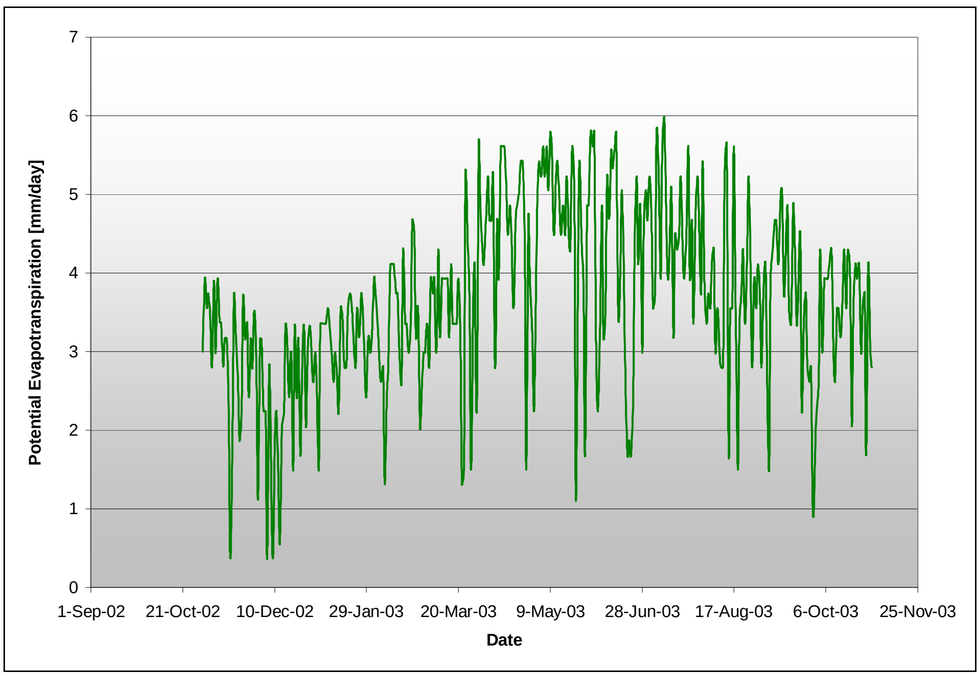


Figure 62 Average potential evapotranspiration reported for S65CW and S65DW by SFWMD

4.4.2 Measured Pan Evaporation

The other measurement of evaporation collected within the SFWMD and a measurement that is commonly used in hydrologic models is pan evaporation. Pan evaporation data is reported on a daily basis; however, the utility of the existing data is limited. As shown in

Table 10, the data available within the DBHydro database is not continuous in time. The breaks in the data coincide with weekends; it is assumed the measurements are recorded in person and are not readily available to SFWMD water managers and operators. Pan evaporation data maybe useful since many land surface models use the pan evaporation data as inputs to the models. However, without the possibility of daily data it would be difficult to input relevant pan evaporation data into the water balance model.

Table 10 Example of Pan Evaporation Data Available

Daily Date	Data Value	Code	Revision Date
1-Nov-02	0.18		10-Feb-03
2-Nov-02		X	10-Feb-03
3-Nov-02		X	10-Feb-03
4-Nov-02	0.49	A	10-Feb-03
5-Nov-02	0.06		10-Feb-03
6-Nov-02	0.28		10-Feb-03
7-Nov-02	0.15		10-Feb-03
8-Nov-02	0.16		10-Feb-03
9-Nov-02		X	10-Feb-03
10-Nov-02		X	10-Feb-03
11-Nov-02		X	10-Feb-03
12-Nov-02	0.62	A	10-Feb-03

4.4.3 Modeled Evapotranspiration Rates

The measurement of pan evaporation and potential evapotranspiration rates within the SFWMD produces point measurements for the estimation of areal evaporation and evapotranspiration measurements. The use of modeled data would provide the geospatial water balance with a continuous estimation of evaporation and evapotranspiration across the water control units and water control catchments within the Three Lakes test area. As discussed in Chapter 2, the Radiation Method for the estimation of potential evaporation produces similar results to the Penman-Monteith equation; however, the applicability of the equation is limited to cattail marshes, open water bodies and shallow surface water sites. The use of the Radiation equation across the SFWMD is possible; however, it relies on point measurements to create a continuous estimation of evapotranspiration. With 25 weather stations across the SFWMD that measure solar radiation the density of gages compared to the potential evapotranspiration measurements is approximately equal. The use of more refined evapotranspiration models may be required in order to capture the differences between the potential evapotranspiration and the actual evapotranspiration rate.

The use of forecasted data for evaporation and evapotranspiration would be of added benefit to the calculation of water storage in near-real time. A source of near-real time weather data available for free use is NARR data. The NARR is the North American Regional Analysis project which is a collaborative effort between the National Centers for Environmental Predication (NCEP), the National Weather Service (NWS), and the National Oceanic and Atmospheric Administration (NOAA) (NARR, 2005). The model provides a large-scale continental-scale weather model for the majority of North America. An investigation of the relevance of the surface evaporation rates and latent heat fluxes predicted by the model would provide the geospatial water balance with continuous evaporation rates from the land surface, both spatially and on a smaller time scale, the NARR model produces three hour average estimates of the predicted values.

To determine the NARR-A evaporation estimate for the C41-A-North water control unit the data was extracted from the NARR-A data set using the data probe. The grid information was then interpolated using inverse distance weighting for each time step; in this case the time step was a month. Zonal Statistics were used to calculate the average evaporation rate over the entire water control catchment. The evaporation data from this analysis is presented in Figure 63. The evaporation data extracted from the NARR-A monthly data indicates an evaporation rate that is lower than the potential evapotranspiration rate measured in the SFWMD at weather stations S65CW and S65DW. The implication that the actual evaporation rate is lower than the potential evaporation rate is consistent with the idea that potential evaporation is not water limited, where as actual evaporation rates are limited by the availability of moisture in the system. In wetter months, such as July and August the NARR-A evaporation rate and the potential evapotranspiration rate are similar, but in drier months, such as November, December, and January the NARR-A evaporation data is much lower than the potential evapotranspiration rate.

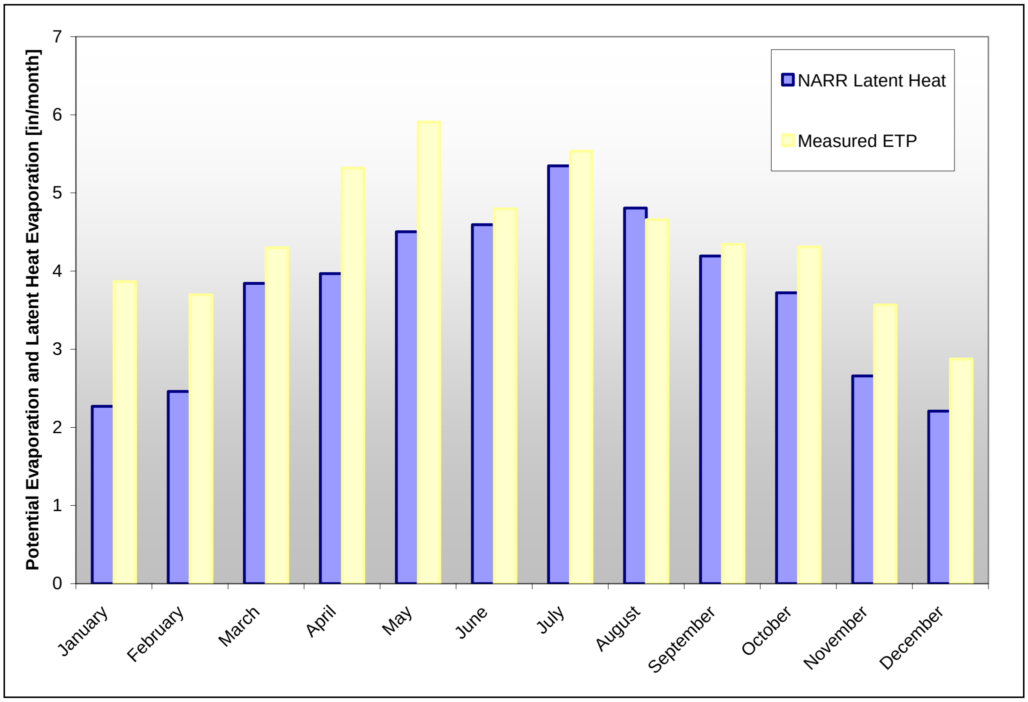


Figure 63 Reported monthly average potential evapotranspiration at weather stations S65CW and S65DW and modeled evaporation data from NARR-A monthly data

The comparing the estimated evaporation from the NARR-A monthly data to the reported potential evapotranspiration rate the total amount of water evaporated using NARR-A data was 1150 mm/yr and using potential evapotranspiration was 1350 mm/day. The difference of 200 mm/yr [7.9 in/yr] is approximately 15% difference between the two estimation methods. A 15% difference in the amount of water evaporated from the ground surface has a significant impact on the calculated amount of water stored on in the water control catchment. Using the evaporation data from the NARR-A and the NEXRAD data for rainfall, the geospatial water balance over the C41-A-North water control catchment produces an increase in the estimate of the volume of water stored. As shown in Figure 64, the amount of water calculated in the water control catchment at the end of the October 2003, is much larger than the amount of water stored in the catchment at the beginning of the analysis.

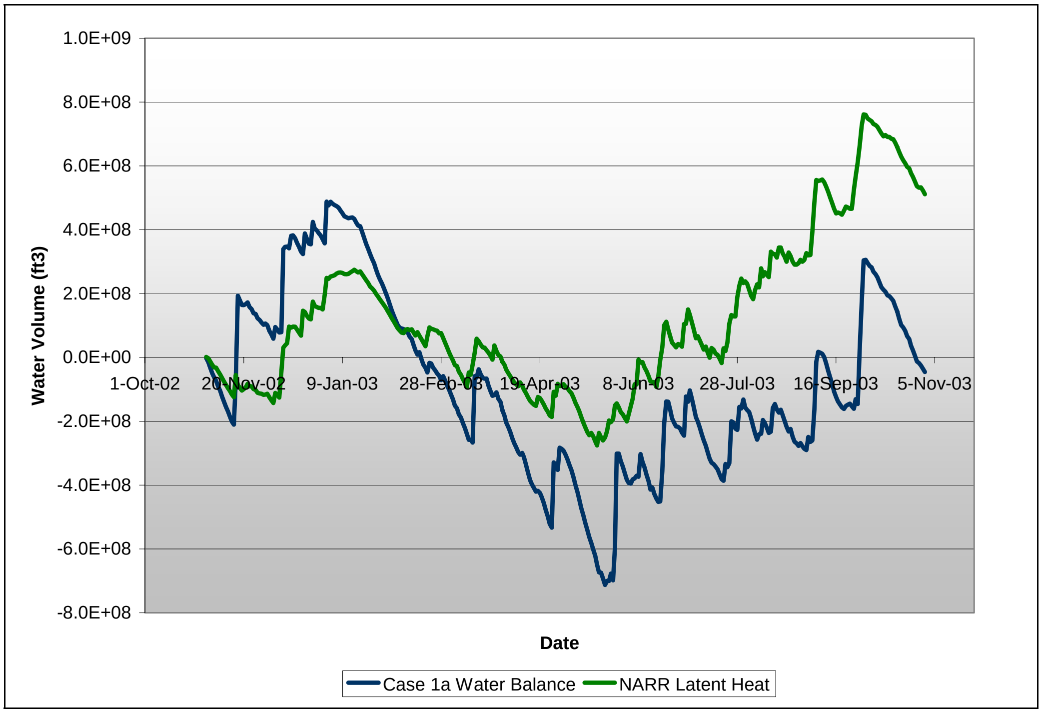


Figure 64 Comparison of Case 1 water balance approach to use of NEXRAD rainfall data and NARR-A Latent Heat evaporation data

The impact of NARR-A data on the geospatial water balance decreases the variability of water stored in the water control catchment over the entire year. The lose of water from the water control catchment in the summer months decreases compared to the original water balance approach of rain gage estimates and potential evapotranspiration data. The fact that the NARR-A data produces an estimate for the actual evaporation rate as opposed to the potential evapotranspiration rate is a step in the right direction; however, there is presently no real-time data that estimates the latent heat in the atmosphere that is easily available to the SFWMD. Therefore, NARR-A data is a potential data set to estimate the actual evapotranspiration rate based on the historic data extracted from the data set. The NARR-A data set has the benefit of not being associated with any specific point in the SFWMD, but as points independent of soil and vegetation type, as well as develop a continuous evaporation estimate over the entire SFWMD.

4.5 Predicting the movement of water between water control units and catchments

To predict the water storage in the water control catchments based on the current set of observed data and modeled data, the transfer of water between the water control units and water control catchments must be calculated. As shown in Section 4.1.1, the transfer of water between the two control volumes can have a significant impact on the overall estimate of the amount of water stored in a water control unit. The transfer of water between the water control units and water control catchments is due to two types of water movement: natural water movement and anthropogenic water movement. Natural water movement includes such phenomena as runoff, infiltration, or seepage. Anthropogenic water movement includes things such as flow due to canal gate openings and pumping. These anthropogenic movements are not easily monitored or modeled due to the transient nature of the water movement. There are more than eleven thousand water permits issued within the SFWMD, with widely varying water amounts allowed to be removed. Even with the issuance of a permit the occurrence of water additions and removals from are not continuous. The transient nature of water addition and removal due to these permits may mean that the transfer of water between the water control units and the water control catchment may not be modeled easily from the information currently available.

If the transfer of water between the water control unit and the water control network is related to the amount of water stored within the water control catchment, then there should be a link between the estimated storage within the water control catchment and the transfer of water from the water control catchment to the water control unit. However, plotting the calculated values of Q_{TRANS} for the C41-A-North water control unit and the calculated water storage within the water control catchment there is no apparent correlation between the two factors, Figure 65.

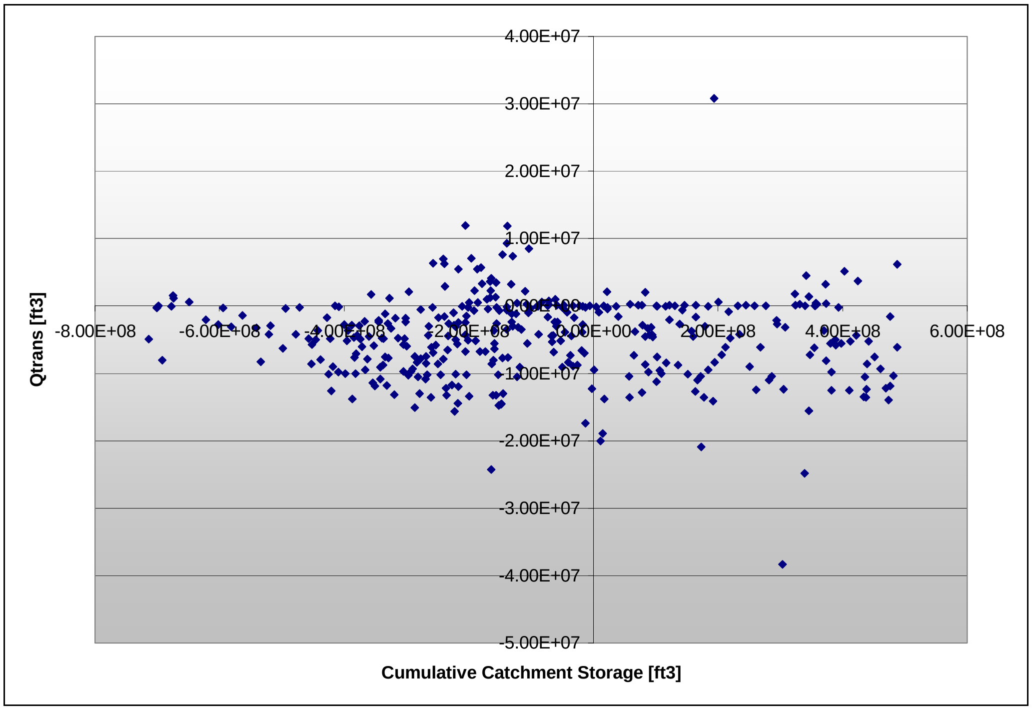


Figure 65 Plot of Cumulative Catchment Storage of water control catchment C41-A-North and the calculated Qtrans

The calculation of the Q_{TRANS} term in the geospatial water balance has a potential large impact on the calculated water volume stored within a water control catchment; however, at the daily time step there is no apparent correlation between the calculated value for Q_{TRANS} and the potential influencing factors: water control catchment water volume, evaporation rate, canal storage, structural flow. For the estimation of near real-time water balance forecasts of the volume within a water control catchment, the movement of water is estimated based on the value of Q_{TRANS}. Thus, if no relationship currently exists then the value of Q_{TRANS} for near-term forecasting cannot be developed. Additional work should be undertaken in more water control units to determine if a relationship exists between Q_{TRANS} and the measured parameters of the geospatial water balance.

4.6 Visualization of Water Balancing in Arc GIS

4.6.1 The TSWindow Toolbar

Once a procedure for the geospatial water balance has been developed, as shown in Sections 4.1 to 4.4, a methodology must be created to display the results of the water balance. The water managers require an easy-to-view and easy-to-interpret graph or gage of the estimated water content contained within a selected water control catchment. The ability to display the estimated water content within a water control catchment is currently not available to the water managers, and is an important link in the development of a water management strategy. The amount of water contained within a water control catchment indicates the need for water or indicates an abundance of water in a water control catchment that could potential enter the operational control units of the SFWMD. Previously, it has been difficult to display time varying parameters within Arc GIS easily and quickly. At CRWR, a software tool has been developed to easily visualize time series within Arc GIS. The software, called Arc Hydro TSWindow tools, uses two input sources: the time series information and the connection between the time series. Water balances are calculated on the fly within Arc GIS with the tool. For the water balance technique to work correctly, the connections between the control volume and the fluxes and flows must be explicitly defined. To accomplish this explicit link between the fluxes and flows, the Coupling Table is created. The Arc Hydro TSWindow toolbar, Figure 66, has two main functions: to plot individual time series for a selected feature within ArcMap, and to plot all the flows and fluxes associated with a control volume of interest. The tool is able to visually plot net inflows, net fluxes, and the overall net inflows for a control volume of interest. There are four main functions available on the TSWindow toolbar: enable plots of Arc Hydro time series, compute fluxes, flows and water balances, specify time period of interest, and create a plotting window within Arc GIS.

Figure 66 Arc Hydro TSWindow toolbar

The first part of the analysis requires the population of the Coupling Table for the C41-A-North water control catchment. The two control volumes contained within an area of interest: the water control unit and the water control catchment must be populated separately. As with the calculation of the geospatial water balance using spreadsheets, the first volume that must be calculated is the estimated storage within the water control unit and then calculate the values for the Q_{TRANS} term for the water control unit. Since the units of the Q_{TRANS} term are in length cubed [ft^3] the values must be associated with a point. To associate the Q_{TRANS} value with a single point representative of the water control unit, the Q_{TRANS} value is associated with the schematic network node for each water control unit.

Once the schematic relationships for the geospatial water balance are developed then the water balance is readily viewable using the TSWindow tool bar.

Once the user selects the type of plot they wish to view, in Figure 67, the plot is displayed the charting area below the Arc GIS map. The user selects the plot fluxes and flows button and selects: Plot Change in Storage. The resulting display in Arc Map shows all of the water control catchments that have water balance information: in this case only the C41-A-North water control catchment has water balance information in the CouplingTable. Selecting the C41-A-North water control catchment the change in storage over each time step is created and plotted. The time it takes to plot the information is only a second. The computation time required to plot the time series information is negligible compared to the computation time required for NEXRAD rainfall estimates for the region.

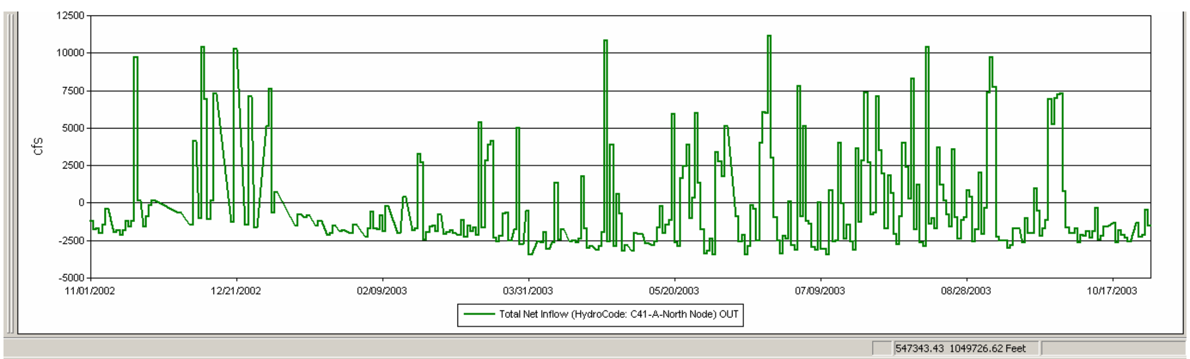


Figure 67 Change in water control catchment storage displayed by TSWindow toolbar

However, the times series plot shown in Figure 67 does not display to the user the trend of water movement into and out of the water control catchment. There is a feature within the TSWindow toolbar to allow the user to accumulate the time series over the time period of interest. However, the tool does not current work on calculated time series. The cumulate tool will work on time series that are stored within the Timeseries table in the geodatabase but will not currently work on time series that are derived using the TSWindow tools. This is an area for future work. The ability to display the longer trend of water movement into and out of a control volume is a useful measure for the SFWMD water manager.

4.6.2 Visualizing the state of the system

Another aspect of the geospatial water balance that was discussed with the SFWMD water managers was the ability to display the state of storage to an operator or water manager. Based on the analysis of the geospatial water balance there are two aspects that would be on interest to a water manager, the amount of water stored in the catchment and the rate at which storage is changing. Several visualization methods were explored; however, at present no method has been identified as the ideal visualization method. Two visualization methods are discussed: plot of storage and change in storage and storage gage.

The first visualization method deals with the display of data using the two variables that describe the state of the system: the volume of water stored and the rate of storage change. Looking at a plot of the geospatial water balance, Figure 68, there are four options for the system: 1 - storage is above average and increasing, 2 – storage is above average and decreasing, 3 – storage is below average and decreasing, 4 – storage is below average and increasing. Plotting the estimated storage value and the 7-day change in storage, the resulting display gives the user an indication of the storage within the water control catchment and the direction that water is moving, into or out of the catchment.

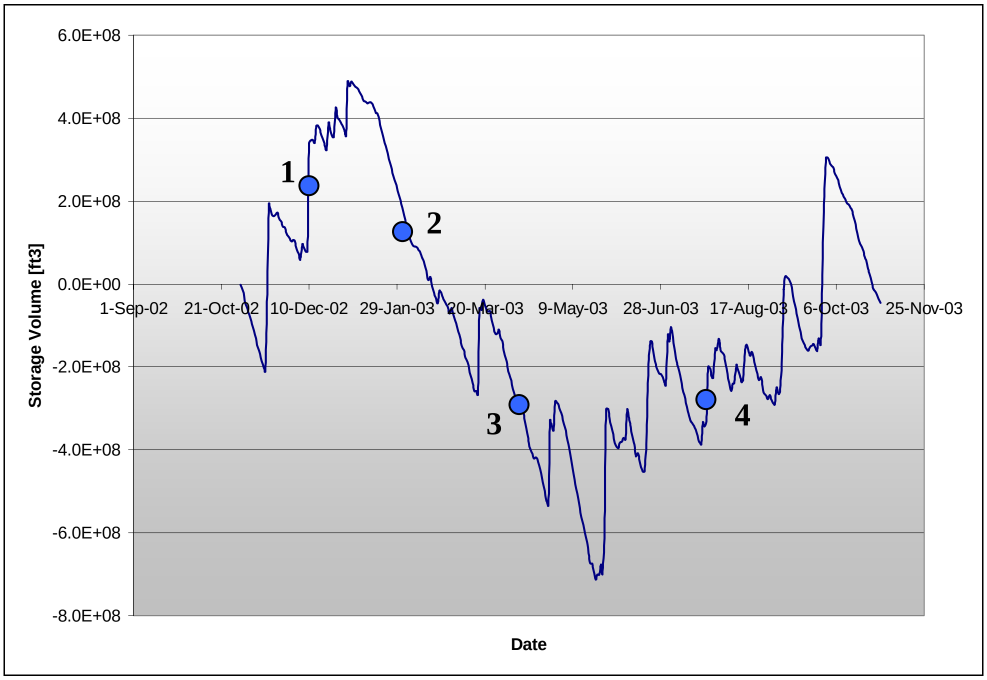


Figure 68 Four types of storage and change in storage for a water control catchment.

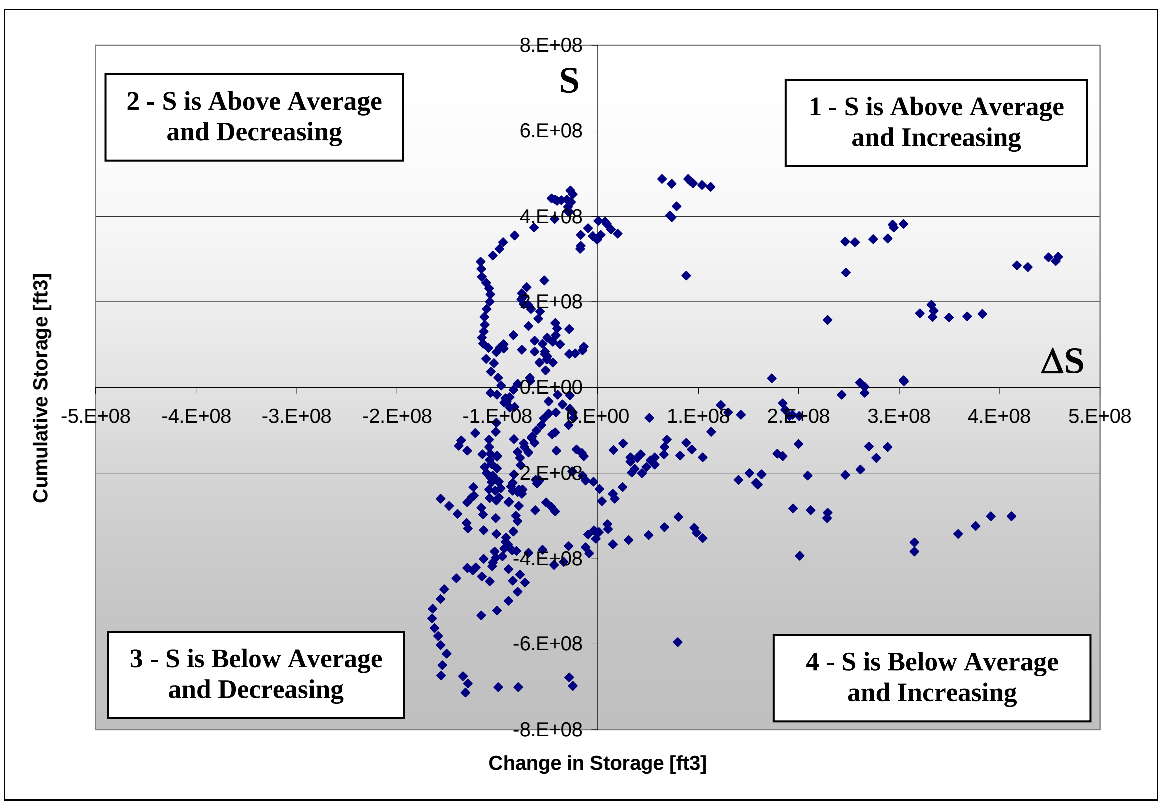


Figure 69 Proporsed plot of type for estimation of the state of a Water Control Catchment

The second visualization discussed was the use of a gage to describe the storage within the catchment, while providing two storage indicators: the capacity of the system for additional rainfall, and the available water in case of drought. An example is presented in Figure 70. This second gage would require knowledge of previous extreme water events to estimate the historic highs and lows. As well, a knowledge of previous 'ideal' operating conditions would be required.

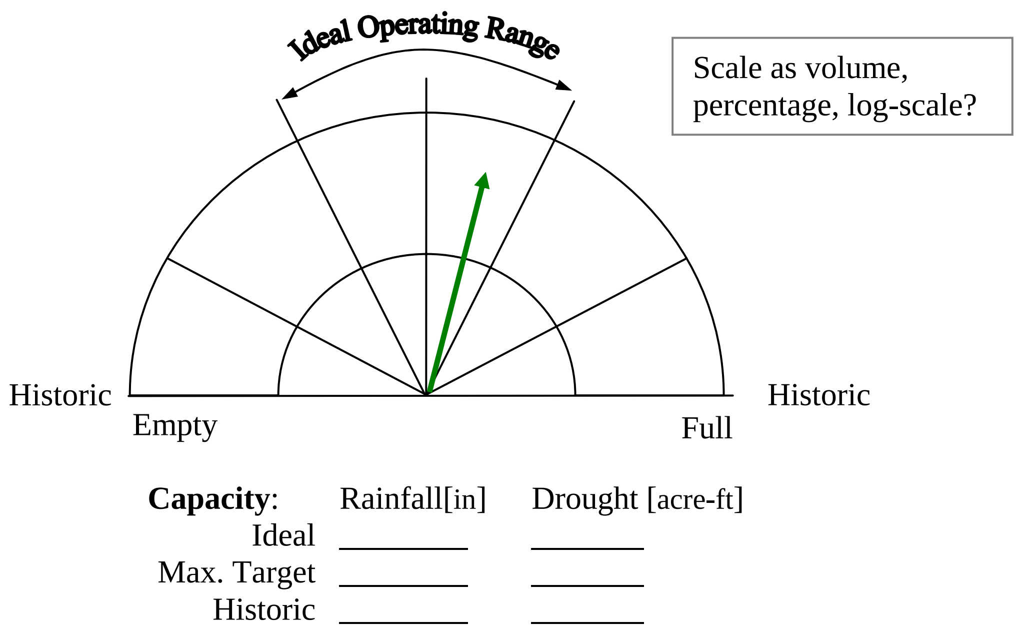


Figure 70 Proposed rain gage format for visualization of water control catchment storage capacity

At this point in the project, there is no clear choice for an indicator of the state of the catchment, additional work should be done with SFWMD in develop an visual representation for the state of a water control catchment.

5 Conclusions

Ron MIireau, the head water manager at the South Florida Water Management District (SFWMD) proposed a simple water balance approach to estimating water stored in the SFWMD. The main objective of this thesis is to create a methodology for calculation the simple water balance proposed by Ron Mireau automatically and within a GIS framework. In the initial part of this project a data model was developed to describe the spatial features of the hydrologic system within the SFWMD. In conjunction with the SFWMD, PBS&J, and CRWR, an Arc Hydro Enterprise Database (AHED) was developed and implemented in a geodatabase design. The AHED is an extension of the Arc Hydro data model. This thesis looked at ways to describe the movement of water through the SFWMD using the defined geodatabase features in the AHED. To describe the movement of water in the SFWMD two new terms were defined: water control unit and water control catchment. A water control unit can be considered the operationally significant portion of the water control unit network, the water bodies control by the SFWMD. A water control catchment is defined as the extent of land surface area that drains into a water control unit.

A geospatial water balance is proposed and investigated in the Three Lakes test area, which encompasses an area surrounding Lakes Kissimmee, Istokpoga, and Okeechobee. The C41-ANorth and Lake Okeechobee water control catchments are two catchments within the Three Lakes test area. The geospatial water balance accounts for the known inputs and outputs to a control volume, either a water control unit or water control catchment, by documenting the direction of water movement between different features in using an Arc GIS software extension, called the Hydrologic Flux Coupler. The Hydrologic Flux Coupler is a table in the expanded Arc Hydro data model which documents the control volume of interest, the source or sink of water movement, and the direction of water movement, either into or out of the control volume.

The time-varying data inputs to the Hydrologic Flux Coupler To develop the geospatial water balance within ArcGIS the Arc Hydro time series format was used. An expanded Arc Hydro data format was developed in conjunction with the SFWMD and PBS&J. The Hydrologic Flux Coupler is based on the Arc Hydro time series format; however, time series information from the SFWMD is not stored in Arc Hydro format. Time series information is presently stored within the DBHYDRO database.

Methodological Conclusions

The Hydrologic Flux Coupler is an excellent approach to automating the geospatial water balance method. Once the links between the documented fluxes and flows are established in the Hydrologic Flux Coupler the only additional requirement is to add time series information into the Timeseries table, in the correct format. The data compellation time and computation time the Hydrologic Flux Coupler is reduces compared to the amount of time required to create an Excel spreadsheet. In particular, the Hydrologic Flux Coupler decreases the amount of time for creating visualizations of the time series information.

The extraction of time series information from the DBHYDRO data is presently time consuming and tedious. The amount of time required tracking down preferred data sets and continuous inputs to the geospatial model prevented the analysis of additional water control catchments within the Three Lakes test area. An output option for the DBHYDRO database is an Arc Hydro time series format would significantly decrease the amount of time required to process time series information from DBHYDRO to the expanded Arc Hydro SFWMD geodatabase.

In addition to the development of the geospatial water balance, an additional analysis of the sensitivity of the geospatial water balance was preformed on the C41-A-North water control unit and catchment for an entire year, November 1, 2002 to October 31, 2003. The results of the data evaluation over the C41-A-North produces conclusions in four areas of interest: rainfall; evaporation and evapotranspiration; calculation of Q_{TRANS}; and estimation of water surface area. The areas of interest are discussed below.

Rainfall

Three different rainfall data sources were analyzed for use in the geospatial water balance: rain gages, NEXRAD, and rainfall rain areas.

- The arithmetic-averaged rain gage data reduced the calculated change in storage in the C41-A-North water control catchment to nearly zero over the year from November 1, 2002 to October 31, 2003; however, the rain gage network does not have near-term forecasting.
- The NEXRAD rainfall data shows an overall trend similar to the rain gage data; however, on certain occasions, it significantly over-estimates or under-estimates the rainfall amount, compared to the observed rainfall data.
- Intense storms, no matter how they are measured can have a long term impact on the geospatial water balance. If a rainfall measurement technique over- or under-estimates rainfall for a single storm event the impact on the water balance is long-term. During study year, the NEXRAD rainfall data under-predicts the rainfall of one storm, from November 16 to 18 2002, by 1.8 inches, compared to rain gage data. This missing rainfall affects the water balance over the remaining year.
- The NEXRAD data has the added benefit of near-time rainfall predictions, which the rain gages do not have.
- For the C41-A-North water control catchment, the rain gage data produces the smallest change in storage in the water control catchment over the year of interest; however, this result may be a coincidence and additional analysis should be conducted on other water control catchments within the Three Lakes test area.
- The rainfall rain areas are not appropriate for use with the geospatial water balance; they significantly over-predicted the rainfall amount within the C41-A-North water control unit compared to both rain gage measurements and NEXRAD rainfall data. There is too much spatial variation over the rainfall rain areas in a day for the rain area data to be used.

In addition to rainfall over the water control catchment, accounting of rainfall directly onto water bodies was investigated. In many models, rainfall directly onto smaller water bodies is ignored. However, the volume of water entering the C41-A-North water control unit due to direct rainfall on the water bodies can amount to 5% of the total volume of water entering this unit. For the Lake Okeechobee water control unit, which covers 80% of the Lake Okeechobee water control catchment, direct rainfall into the lake can amount to 5.6 times greater volume than water passing through surface structures.

- Rainfall directly onto water bodies cannot be uniformly ignored in the SFWMD.
- However, the rainfall estimation technique for rainfall on smaller water bodies does not have a significant impact on the water balance; in particular, it does not have an impact on the calculation of Q_{TRANS}.

For the calculation of NEXRAD rainfall amounts for each water control catchment three different raster cell sizes were compared (500 m, 250 m, and 100 m) to determine the impact of raster cell size on rainfall estimates.

- It is recommended that the 500 m raster cell size be used for processing NEXRAD data due to the face that it processes the fastest and produces almost identical results to the 250 m, and 100 m grids.

Evaporation and Evapotranspiration

Three data sources were identified and analyzed for evaporation and evapotranspiration inputs to the geospatial water balance: potential evapotranspiration, pan evaporation, and the North American Regional Reanalysis (NARR-A) latent heat data. The following conclusions were developed based on the use of each data set in the geospatial water balance.

- Pan evaporation data is not readily available; thus, it is not an appropriate data set for the geospatial water balance.
- The potential evaporation data is available on a daily basis, is readily accessible, and recommended by SFWMD; however, it is only valid in areas where evaporation is not limited by moisture. Therefore, has the potential to over-

predict evaporation from land areas. The decrease in actual evaporation is most noticeable in winter months, when less rain falls and the landscape dries out.

- NARR-A latent heat information produces data that is lower than the potential evaporation data. The evaporation rates in the summer, based on the NARR-A data are equivalent to the potential evapotranspiration rates, this is agreement in flux magnitude indicates that evaporation occurs at the potential evapotranspiration rate in summer months. However, in winter months, when the soil dries out the actual evaporation rates are lower than the potential evapotranspiration rates reported by the SFWMD. This data set has the potential to provide estimates for evaporation over a continuous region that is independent of soil type.

The evaporation of water from a free surface cannot be ignored, particularly for larger water bodies; evaporation from Lake Okeechobee can be 3 times greater than the amount of water entering the lake from SFWMD operated surface structures.

- Potential evaporation rates are appropriate to estimate the evaporation rate from free water surfaces.
- NARR-A data and the real-time model results from the National Center for Environmental Prediction are an appropriate estimate for evaporation data for the water control catchments

Calculation of Q_{TRANS}

The amount of water stored in a water control catchment is calculated based on the rainfall into the catchment, the evapotranspiration out of the catchment, and the transfer of water between the water control unit and the water control catchment. The amount of water transferred between the water control unit and catchment is calculated in a term called QTRANS, which is the amount of water transferred between the water control unit and catchment. The calculation of Q_{TRANS}, which is not directly measured, is dependent on observed data, such as rainfall and canal volume.

- Regardless of the rainfall estimation technique, the resulting estimate for Q_{TRANS} was within 0.3% of the initial estimation technique.

- The method used to calculate the canal volume does not change the estimate of Q_{TRANS}; therefore, it is recommended is the Simplified interpolation method.

Since QTRANS is the unknown variable, the ability to predict Q_{TRANS}, based on known or predicted values would be helpful for predicting near-time water transfer amounts. However,

- There is no correlation between Q_{TRANS} and any factor in the geospatial water balance, rainfall, potential evaporation, or structural flow in the water control catchments analyzed.
- Additional analysis of this variable are required, either on different water control units or on a different time-scale.

However, the difference in the cumulative estimates for Q_{TRANS} when using averaged rain gage estimates and Rain Areas rainfall data is only 0.3% over an entire year. Therefore, it is important to include rainfall estimates directly onto the large water bodies. For smaller water bodies, such as canals, it is not important what rainfall estimation technique is used.

Estimation of Water Surface Area

There were two sources of information to estimate the water surface area: canal geometry and 24K NHD polygons data that describe the water surface area. Comparing the estimates of the water surface for C41-A-North, based on hydraulic calculations and the 24K NHD data set, there is only 4% difference between the two estimates. The 24K NHD data set as the added advantage of being based on observed data; therefore,

- The 24K NHD polygons are an appropriate estimation of the water surface. This information is a significant improvement from the 100K NHD line work, which does not have the capability to estimate surface area of a water body.

6 Recommendations

There are two types of recommendation, improvements of the Arc GIS technique to implement the visual representation of the geospatial water balance and improvements associated with the development of inputs to the geospatial water balance. With respect to the visualization of the geospatial water balance within Arc GIS the following points of study are recommended:

- Continued development of the TSWindow toolbar to allow for the display of cumulative water balances over a selected control volume.
- The most computationally intensive portion of the visualization problem will be the formatting of data from the native format to the Arc Hydro time series format. Automation of the formatting process is required to decrease the amount of time a user must interact with the data. The ability to extract DBHYDRO time series information in Arc Hydro time series format would decrease the formatting time for the geospatial water balance.
- At present, a gage representation of the state of the water control catchment storage capacity has not been developed, thus additional input is required from the SFWMD water managers to develop a gage that provides a visual indication of the storage of the water control catchment.

If additional analyses of data inputs to the water balance are required the following suggestions are recommended.

- NEXRAD rainfall data is recommended for the estimation of rainfall for the SFWMD. It contains the spatial variability desired for the geospatial water balance and shows similar temporal trends as all other forms of areal precipitation estimates test in this document.
- The use of 500 m NEXRAD grids is appropriate for the development of the geospatial water balance for the Three Lakes test area if the present calculation method is used. However, it is recommended, due to the computation time required to produce a rainfall estimate using NEXRAD data that a vector method be used to calculate rainfall estimates for water control catchments.

- To estimate the near real-time water control catchment volume storage an estimate in the amount of water transferred between each water control catchment and water control unit, Q_{TRANS}, is required; thus, additional work on smaller time scales is recommended to determine if there is a model applicable for the movement of water between the two control volumes.
- As part of the requests for project development the SFWMD would like to see the geospatial water balance expanded to a smaller time step. Therefore, it is recommended that the geospatial water balance study examine the impact of decreasing the time step from daily to hourly or 15-minute data.

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Appendix A

Geospatial water balance Memo by Ron Mireau

DRAFT
Operational Water Budget Accounting
Ronald Mierau
4/1/2004

A simple water budget approach is required for the purpose of facilitating water management decisions. The objective of the water budget approach is to quantify WCU catchment storage such that it provides an index to the hydrologic state of the water control unit. This index is useful in predicting when water supply deliveries will need to be made, when water will need to be removed from the water control unit, and a qualitative indication of the magnitude of the flows involved. An additional qualitative Quality Control benefit could be derived from archiving the resulting storage component along with the calibration criteria used to derive the storage since residuals since measurement errors are included in the resulting data stream.

Currently this function is performed by water managers in a rather informal manner through general observation of rainfall, observation of water levels, flow rates, and flow directions with these observations at times supplemented by “back of the envelope” calculations and review of past conditions.

It is possible to use a water budget approach to improve and automate this effort. The basic concept is to account for all inflows, outflows, and storage terms for two separate components: 1. the water bodies that compose each Water Control Unit (WCU) and 2. a separate linked budget for the remainder of the water control catchment area that is outside the water bodies (CATCH). The component we want to track is the change in storage in the catchment area – more precisely, the accumulated change in storage for the catchment area. This change in storage will be affected by irrigation withdrawals, non-regional reservoir operations, flood control operations on secondary drainage systems, changes in groundwater, and errors in estimating or measuring the remaining water budget components. This budget would need to be maintained on a real-time basis and a separate facility to reset the accumulator for the catchment storage and to track the timing, magnitude, and direction of adjustments in order to provide feedback for tuning estimation parameters. It is envisioned that a qualitative indicator of accumulated storage will be adequate for operational purposes but a quantitative historic record will be useful for tuning the estimation procedures to remove long-term bias.

The operational component is envisioned as a dial gage with a pointer that varies from 100% full to 100% empty. In the midrange nothing is happening in that no inflows or outflows are required to keep the same water level in the water bodies that comprise the WCU (no storage change in the water bodies). When the catchment storage decreases sufficiently (primarily through the ET process), water levels in the WCU water bodies will begin to fall and/or water will be brought into the WCU as INFLOW (at a measurable rate) to maintain the water levels. Similarly, when rainfall raises catchment storage sufficiently, runoff will cause the water to be removed from the WCU water bodies at a measurable rate to maintain water levels in the water bodies. These change points from water supply to drainage can be used to provide real-time calibration of the accumulator storage gage and remove cumulative residual errors in estimating water budget terms. In the case where the WCU water bodies occupy nearly all of the WCU catchment (like Lake Okeechobee) the accumulator would not be useful operationally but would track long term cumulative water budget errors for subsequent calibration improvements.

In Mathematical terms

For the Water Bodies that comprise the Water Control Unit:

StorCATCH = RainCATCH – ETCATCH + QTRANS

And

Gage = summation-over-time of StorCatch (scaled to +/- % full scale)

Gage is the operational tool desired

RainCATCH is the rainfall volume (within a small time interval – say 1 or 2 hours) that fell on the WCU catchment area– the rain which fell of the water bodies that comprise the WCU - can use GIS tools to estimate form gage adjusted radar rainfall.

ETCATCH is the evapotranspiration within a small time interval that occurred over the WCU catchment area (water bodies excluded). Daily mean values of pan evaporation multiplied by a coefficient can be used as a first approximation with the estimate distributed over the daylight hours in an appropriate manner. The scaling coefficient could be set to provide a yearly balance of between inflow (rainfall + imported water) and outflow.

QTRANS is the computed water transfer from the water bodies composing the WCU to the Catchment Storage. This is computed as the residual of a water balance for the water control unit as described below.

For the Water Control Unit (WCU)

QTRANS = QIN -QOUT – StorWCU +RainWCU – ETWCU

QTRANS is defined above

QIN = MEASURED Surface water flow volume from Inflow Junctions

QOUT = MEASURED Surface water flow volume to Outflow Junctions

StorWCU = MEASURED Storage Change in the WCU water bodies. Storage in the water bodies computed from the water elevation at the end of the time step less the storage in the water bodies computed for the water elevation measured at the start of the time step.

RainWCU = MEASURED rainfall directly on the water bodies which compose the WCU. Will normally be relatively small since surface area covered by the water bodies that make up the WCU are usually small compared with the area associated with the Catchment area. It is large in a few cases (like Lake Okeechobee)

ETWCU = ESTIMATED evapotranspiration directly from the water bodies which compose the WCU. Will normally be relatively small since surface area covered by the water bodies that make up the WCU are usually small compared with the area associated with the Catchment area. It is large in a few cases (like Lake Okeechobee)

For the Combined Budget

These two equations can be combined for operational purposes:

StorCATCH = RAIN – ET + QIN – QOUT –StorWCU

Where RAIN is the total rain that fell within the WCU catchment boundaries during the time step

ET is the total evapotranspiration from all elements within the WCU catchment boundaries during the time step

The terms on the right can all be measured or estimated.

A running total of the term on the left can be maintained. If there is no long-term bias terms introduced, the value of this total will normally remain between +15 inches and -15 inches when scaled to area of the WCU catchment. Percent full / Percent empty can be computed using this scale range. Alternatively, if recalibration for bias is desired less often, the scale can be increased somewhat.

Appendix B

Glossary of Definitions provided by SFWMD

Glossary

Association: 1. A correlation between a state and a conclusion, a condition-action pair being a rule. Often empirically derived. 2. A correlation between two objects.

Close loop control algorithm:

Constraint: The threat or use of force to prevent, restrict, or dictate the action or thought of others. The state of being restricted or confined within prescribed bounds. One that restricts, limits, or regulates; a check. The state of being constrained [syn: restraint] .A device that holds someone or something back from action [syn: restraint]. The ad of constraining

Control Selector: Control Set:

Control structure:

Current Objectives: Current State: Desired State:

District structure:

Domain: An area about whim knowledge exists.

Domain knowledge: Expert knowledge of a specific subject. Not mathsy.

Dynamic: Of, or related to, systems whose future state is consequent upon their past & present states; that is, relating to systems who have a history .Contains differential or integral expressions. Not static. but may be time-varying.

Flashboard: A board or structure of boards extending above a dam to increase its capacity.

Flow rate: The amount of fluid that flows in a given time through a pump or a gate.

Granularity: The size of the divisions in the variable space. cf precision.

Hydrologic condition: The properties, distribution, and effects of water on the earth's surface, in the soil and underlying rocks, and in the atmosphere.

Hydraulic head:

Measurement: The process of ascertaining the attributes, dimensions. extent, quantity, degree or capacity of some object of observation and representing these in the qualitative or quantitative terms of a data language. Any empirical pursuit that places the observer outside his object of observation must consider measurement the fundamentallXOC8SS through whim scientific constructs or models are linked to reality *(see* index, symptom). Otherwise measurement is only one section in a circular process of computing a stable form. The traditional levels of measurement are nominal, ordinal, interval and ratio scales. (Krippendorff)

.Measurement Set:

Model: 1. An executable description of a system or body of knowledge. 2. The execution of such a description; that is, description + the inference engine = model.

Modeling primitives: The set of basic descriptors used in model construction. Legal operations within the chosen ontology. Objective graph:

Objective Manager: Objective Set:

Operational plan:

Operational regulation:

Operational rule: Identifies a set of actions that will be taken when and if some operational condition, defined in terms of a logical combination of operational states, occurs.

Operational state:

Operational strategy:

Operational zone: Defined ranges of state variables during specified time period; defined in terms of objective graphs, may be as simple as (constant) low- and high-level alert and danger zones, or as complex as the seasonal operations schedule for Lake Okeechobee

Operator: The person in charge of carrying the day-to-day activities and monitoring the .system.

Parameter: A non-dynamic entity. That which determines the structure of a system. Parameters themselves can be changed by inputs, but usually the parameters determine how input will be transformed into outputs. In the linear equation y = ax + b, the slope "a" and the y-intercept 'b" are the parameters; "x" is the independent variable and 'y" the dependent variable. (Umpleby) (2) In computer science parameter is an entry in a command or routine that must be replaced with specific data prior to execution. (Arbib) (3) In a system theory parameters are used to distinguish between systems that are described by similar sets of equations-the choice of parameters fits the model to a specific situation. (Arbib). That what distinguishes between systems of the same organization. The input to a system which determines its mode of operation and thus defines what kind it is. In modelling, a value, usually a coefficient in an equation, that can be made to vary across different models with otherwise similar structure or across different simulations by the same model but is constant in each application. The choice of parameters allows an experimenter to fit the model to a given situation. (Krippendorff)

Rule: A subtype of association; a condition-action pair.

RUP: Rational unified Process is a methodology for software application development. **SCADA**: Supervisory Control And Data Acquisition; Systems are used in industry to monitor and control plant status.

Soft input: Subjective information that needs to be interpreted and analyzed by an .expert in order to produce objective input to a system,

State: The smallest set of information required, along with model & parameters, to uniquely describe everything about a system. The state of a system at a given instant is the set of numerical values whid1 its variables have at that instant. The smallest set of information required, along with model & parameters, to uniquely describe everything about a system. [CONTROL SYSTEMS] A minimum set of numbers which contain enough information about a system's history to enable its future behavior to be computed. [PHYSICS] The condition of a system which is specified as completely as possible by observations of a specified nature, for example, thermodynamic state, energy state.

State Analyzer:

State estimate:

State Estimator: [CONTROL SYSTEMS] A linear system B driven by the inputs and outputs of another linear system A which produces an output that converges to some linear function of the state of system A. Also known as observer; state observer .

State space: [CONTROL SYSTEMS] The set of all possible values of the state vector of a system. The set of possible states in a system.

State transition matrix: [CONTROL SYSTEMS] A matrix I(t,t0) whose product with the state vector x at an initial time t0 gives the state vector at a later time t; that is, x(t)=q. (t,t0)x(t0).

State variable: [CONTROL SYSTEMS] One of a minimum set of numbers whid1 contain enough information about a system's history to enable computation of its future behavior.

State vector: [CONTROL SYSTEMS] A column vector whose components are the state variables of a system.

Storage recharge:

System: a set of variables selected by an observer. (Ashby, 1960). Any definable set of components. (Maturana and Varela, 1979) Any portion of the material universe which we choose to separate in thought from the rest of the universe for the purpose of considering and discussing the various d1anges which may occur within it under various conditions is called a system. (J. W. Gibbs, from his biography by Muriel Rukeyser, page 445) An interacting, or interdependent, group of entities.

System variable:

Variable: A entity whid1 may assume anyone of a set of values. A measurable quantity whid1 at every instant has a definite numerical value. If there is any doubt whether a particular quantity may be admitted as a variable, use the criterion whether it can be represented by a pointer on a dial. Pressure, angle, electric potential, volume, velocity, mass, viscosity, population, national income per capita and time itself, to mention only a few, can all be specified numerically and recorded on dials. Eddington's statement on the subject is explicit: "The whole subject matter of exact science consists of pointer readings and similar indications. Whatever quantity we say we are 'observing', the actual procedure nearly always ends in reading the pointer of some kind of indicator on a graduated scale or its equivalent. "

Variable Space: The set of possible values which may be taken by variables. –

Water control device:

Water control facility:

Water control Unit: may be visualized as the skeleton of a watershed. They are defined as an aggregate of water bodies that are controlled as a single unit.

Watershed: The line of division between two adjacent rivers or lakes with respect to the flow of water by natural channels into them; the natural boundary of a basin.

Water Manager:

Appendix C

Creation of ODSS Schematic Network

Creating Schematic Network for the Water Control Unit Network
Alicia Fogg
CRWR, University of Texas

The purpose of this document is to allow a user create a geometric network for operationally significant HydroEdges to a new feature class called WCULink, along with schematic nodes called WCUNodes. The WCUNodes are inputs and outputs to the Water Control Unit System and thus the WCULink features.

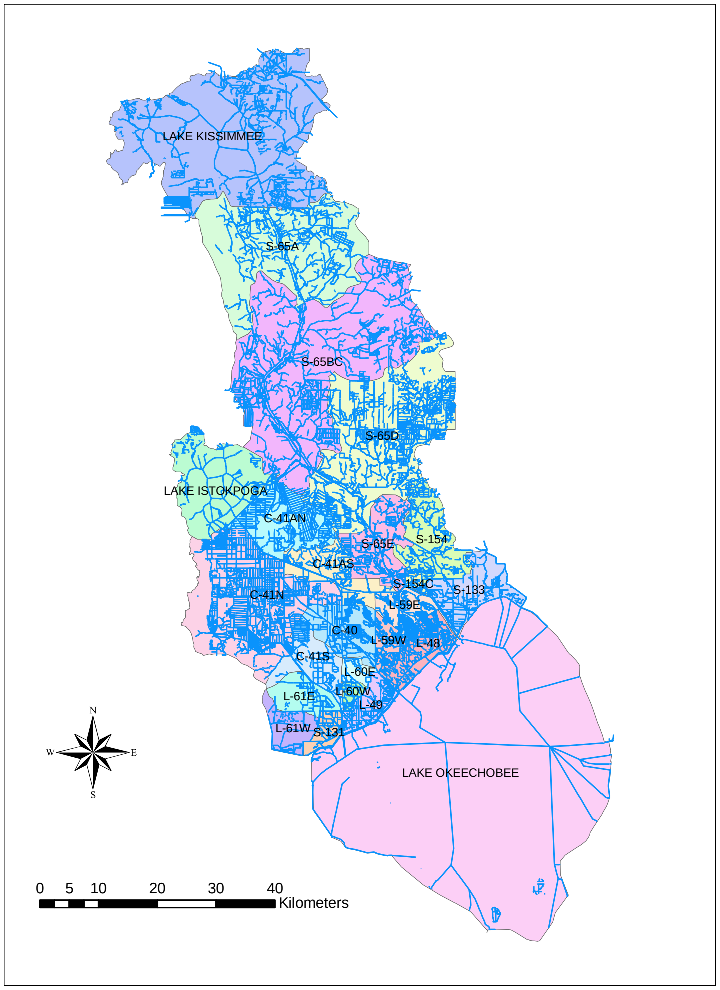
However, if the migration of data from the HydroEdge data set is not required then the user will follow the instruction to create a geometric network shown in the second part of this document, creating Geometric Networks, steps 9 through 13.

There are 13 Steps to migrate from the HydroEdge Network to the WCULink and WUCNode geometric network. They are:

1. Select Operationally Significant HydroEdges from HydroEdge feature class.
2. Export selected HydroEdges to a new feature class, WUCLinksNew.
3. Add 2 fields to feature class, WCUID (long integer) and WCUName (20 characters string).
4. Select the HydroEdges that describe a single WCUCatchment
5. Calculate WCUID and WCUName for the selected line segments, repeat until all the line segments are been given a WCUID and WCUName.
6. Query WCULinkNew to ensure all line segments have been labeled.
7. Dissolve WCULinkNew feature class to new feature class WCULink.
8. Add all the appropriate fields to meet the feature class requirements for data layout.
9. Add WCUNode features.
10. Add additional WCULink features.
11. Build Geometric Network.
12. If errors exist is geometric network delete the network and fix the errors. Steps 9 and 10 until the geometric network is built without errors.
13. Assign flow directions and ensure network is connected.

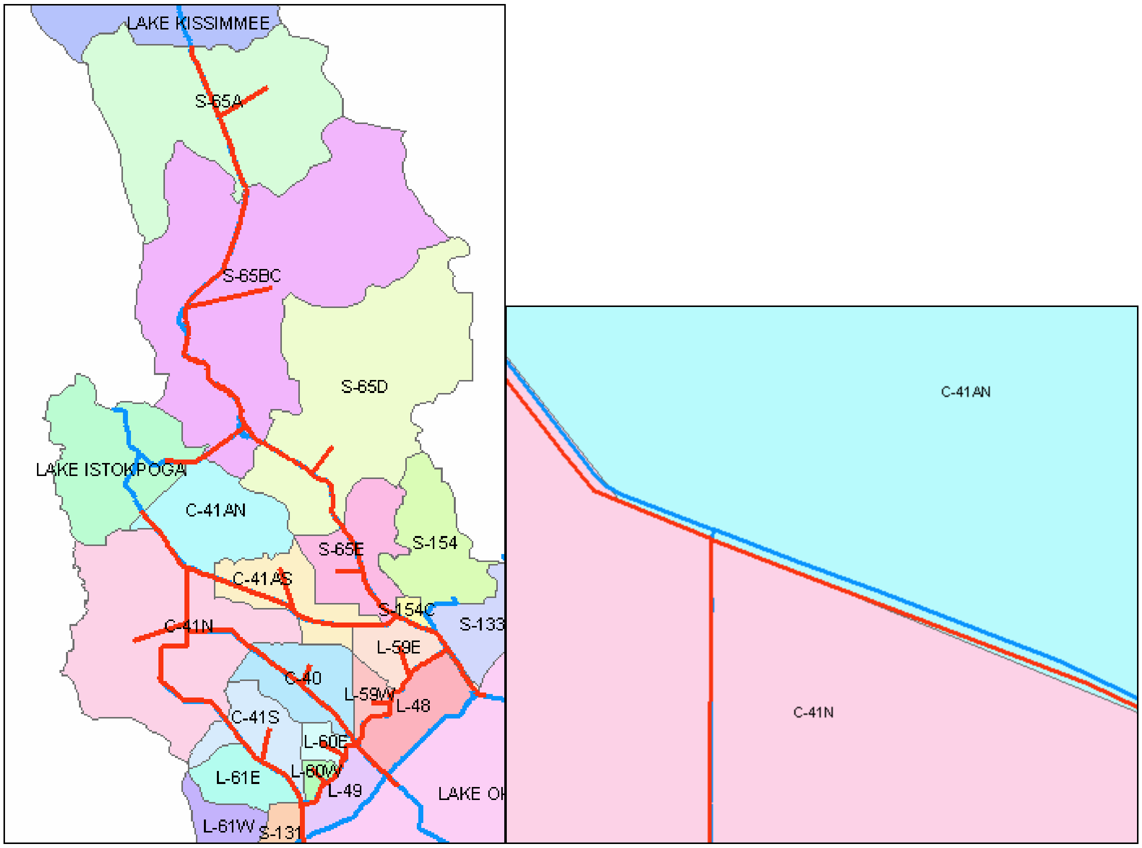
Create WCULink Features from HydroEdge Network.

The HydroEdge feature class is based on line work created for the National Hydrography Dataset (NHD). The NHD in the Three Lakes Region is from the newly created 1:24,000 resolution data set. An example of the dataset is shown below. The density of the line work makes is so high that drawing useful information about the water network in this region is impossible.



Therefore, the South Florida Water Management District has added a field to the HydroEdge Feature Class called Operations1, which is populated with an integer value. Currently, if the field is populated with an integer 1, then the HydroEdge is operationally significant, and part of the operational water network. If the field Operations1 is populated with a 2, then the HydroEdge is not part of the operational water network, and is generally of secondary importance.

Comparing the operationally significant HydroEdges and the feature Class WCULink, there are some disparities between the two feature classes. In order to unify the spatial features of the two feature classes the NHD HydroEdges are taken as spatial correct and the WCULink can be modified to fit the spatial features of the HydroEdge feature class. An example of the disparity between the two feature classes is shown below. The HydroEdges are in blue and the WCULinks are in red.

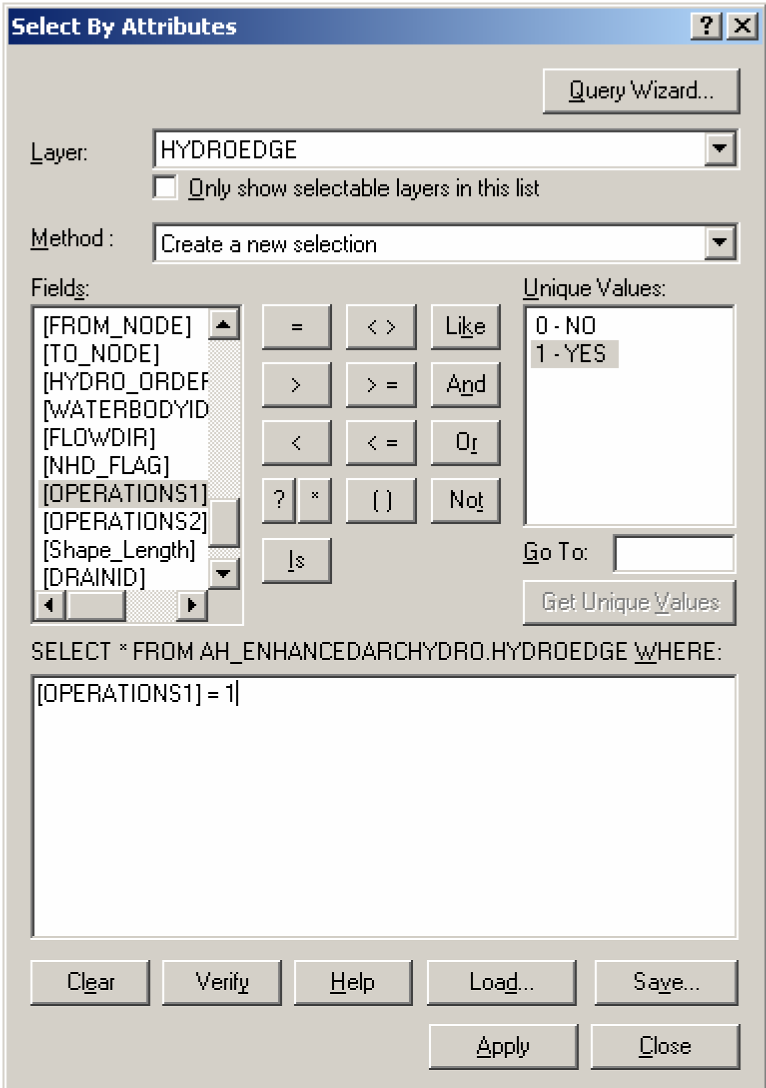


1. **Create WCULink from Operationally Signficant HydroEdges**

First, the user must select the operationally significant HydroEdges. Click, **Selection, Select by Attribute**. In the window, select the **Layer as HydroEdge**, **Method** as **Create a new selection**.

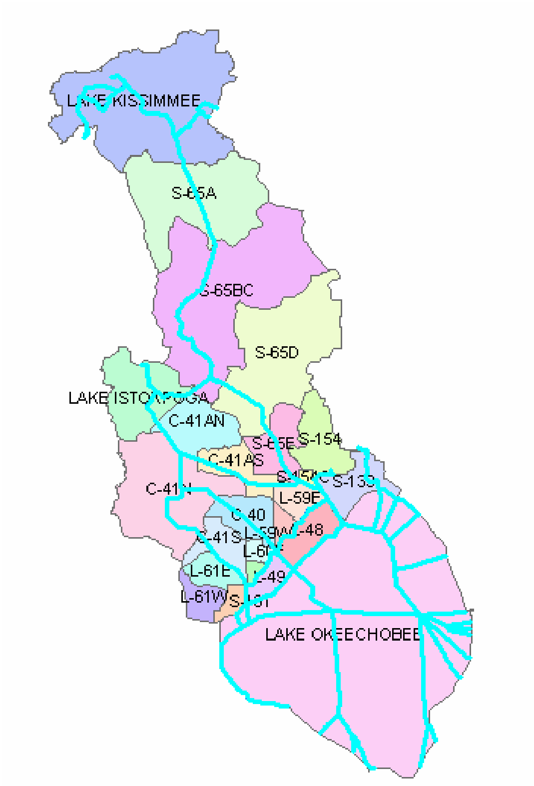
Create the Query in the box as **[OPERATIONS1]=1**.

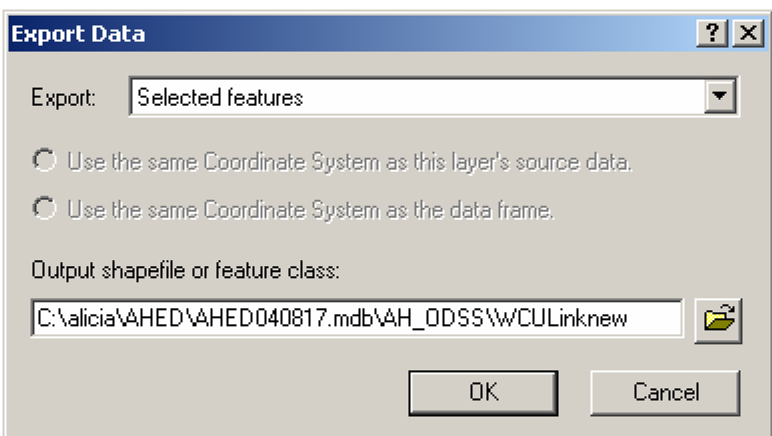
Click Apply. Close the Window. This will select all of the HydroEdges that are currently deemed operationally significant.



2. **Export HydroEdges to new feature class**

The selection should look like the data selected below. The selected features can now be exported to a new feature class, which will eventually become the WCULink feature class. To export the data set, in the Table of Contents, right click on the feature class HydroEdge, select **Data\Export Data**.

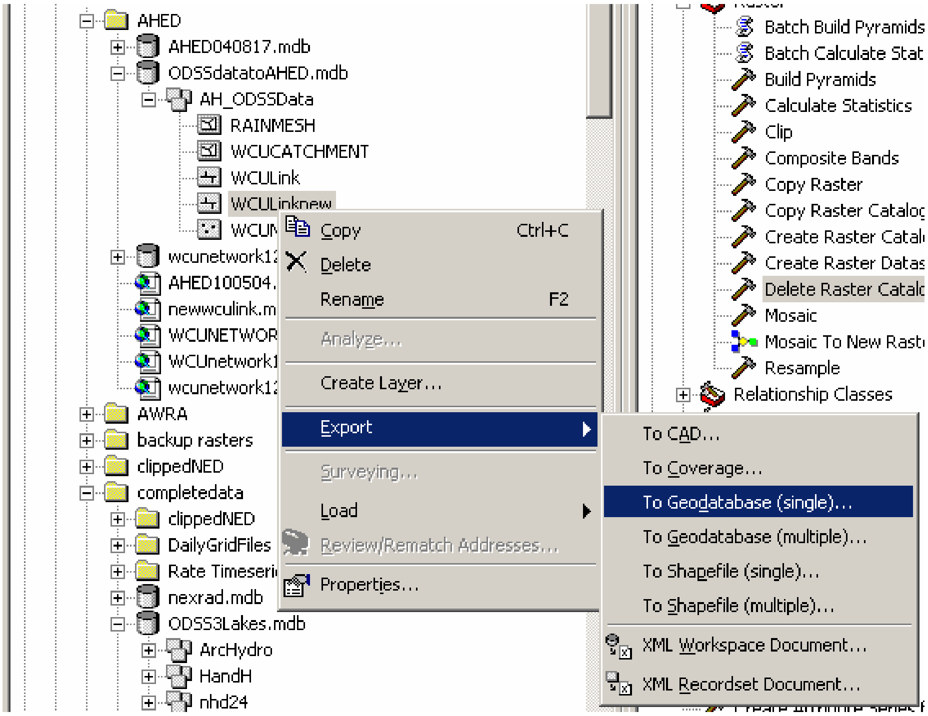




In the Export Data window, select Export **Selected feature**, export using the same Coordinate System as this layer's source data. Output the shapefile or feature class as WCULinkNew in the desired feature dataset. Make sure to save the **exported data as a personal geodatabase feature class**. The exported data cannot be saved to the same personal geodatabase that you are working in; therefore, you may have to temporally save the exported data to another personal geodatabase.

Save the map you were working on in ArcMap, as WCUnetwork.mxd. Start ArcCatalog.

In ArcCatalog, navigate to your newly exported HydroEdge featuress, called WCULinknew. Right click on the feature class, select **Export,** click **To Geodatabase (single)**.



In the window that appears, select the **output location** for the feature class as **AHED\AH_ODSS** and the output **feature class name as WCULinkNew**. Renaming the feature class will keep the new feature class consistent with the terminology developed in the AHED geodatabase. Click **OK**. Click **Close** when the program is finished running.

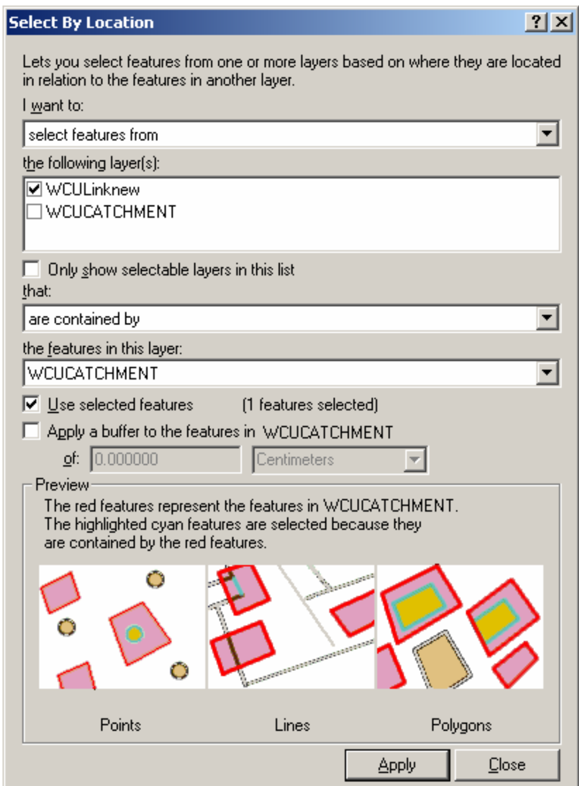
3. Add Additional Fields to Feature Class

Some of the fields contained within the exported feature class are not required in the feature class WCULink; you can remove these fields either now or at a later time. I left the extra information in the feature class until the last moment. Two fields need to be added to the feature class, to hold the WCUID and the WCUName. The values in these two fields will be used to dissolve all of the current WCULink line segments into fewer segments. Within Arc Catalog open the Attribute Table for your line feature class. Select **Options**, **Add Field**, and insert a long integer field, WCUID, and a string field, WCUName, with a length of 50.

Close Arc Catalog.

4. Select Line Segments for Each WCUCatchment

Open Arc Map.
The next step to develop the schematic links for the schematic network is to determine which WCULink line segments fall within each Water Control Unit. This was done based on the location of the WCULink lines that fell within the each WCUCatchment feature and the location of structures that define each Water Control Unit. To select line segments by location select a WCUCatchment using the Select Features tool, then click on **Selection**, **Select by Location**. This brings up the Select by Location menu as shown below:



You will want to select the options from the menu; **select features from WCULink** (your line feature class) that **are contained by** the selected **WCUCatchment** feature. Select **Apply**.

This selection query will select all of the line segments in the WCULink feature class that are completely contained by the selected WCUCatchment feature. While keeping the queried line segments selected zoom to the ends of the selected WCUCatchment and determine if any additional line segments need to be selected. Based on current definitions of WCUCatchments and the location of the operationally significant line segments, there may be some line segments which do not completely fall within the selected WCUCatchment feature but are still part of the Water Control Unit. Add any additional line segments to the queried line segments by holding down the shift key and selecting each additional feature.

5. Calculate WCUID and WCUName Fields

Once all of the desired line segments have been selected, open the Attribute Table. Right click on the field **WCUID** and select **Calculate Values**. In the menu, enter in a WCUID. Make sure to enter the information into the table as an integer value. Each WCUID must be unique for each water control unit; this number will be used for identification purposes later on. Next right click on the field **WCUName**. Select **Calculate Values**. Enter the name of the appropriate name of the WCU, ensuring that the name is entered as a string. Selecting all of the desired line segments before entering the values will the data entry process much faster.

Repeat this process for each WCUCatchment.

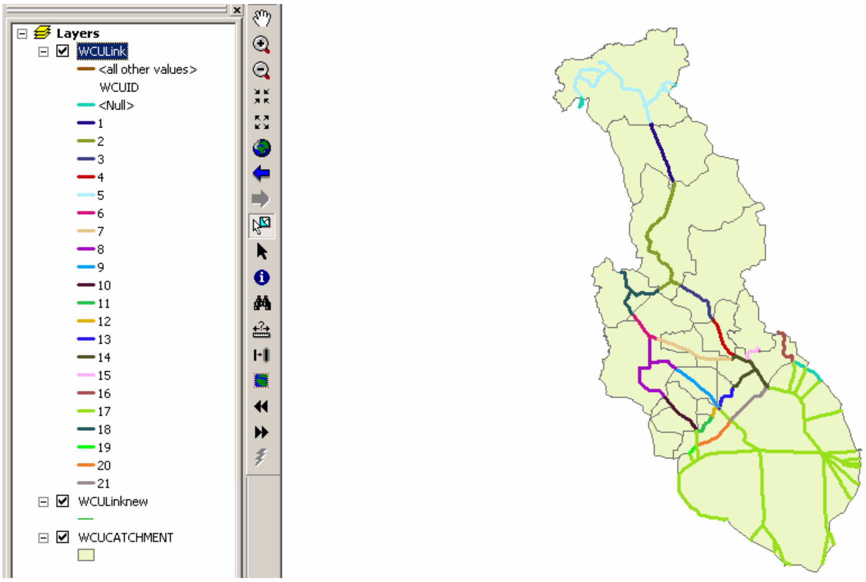
Save Edits.

6. Query WCULinkeNew for all non-Labeled Features

Once you have completed this process, check to make sure that all line segments have a WCUID and a WCUName. This call be accomplished by selecting, **Selection**, **Select by Attribute** from the main menu. Build a query for the WCULink feature class such as the one listed below:

[WCUID]=NULL

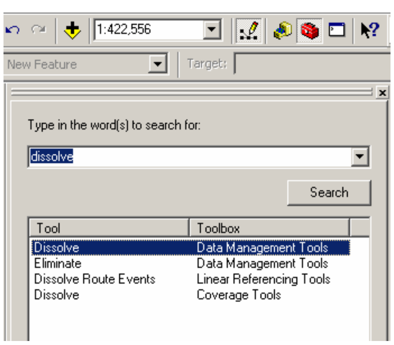
Repeat this process until all of the features have WCUID's and WCUNames. At this point I had approximately 600 different line segments in 21 different WCUCatchments, looking something like this:



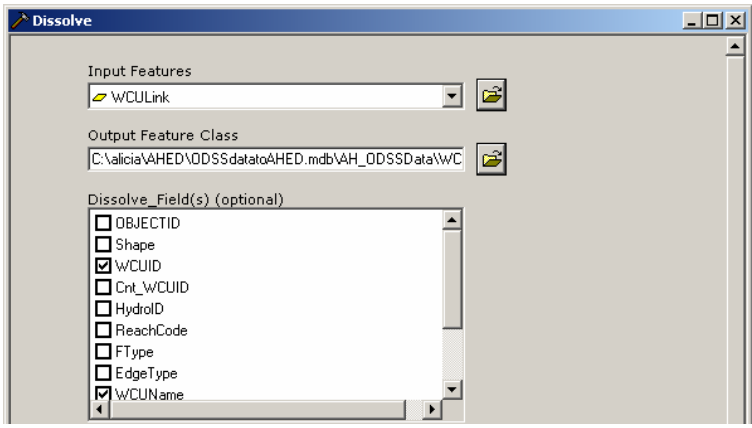
7. Dissolve WCULinkNew

At this point dissolve the WCULink features based on the WCUID and WCUName. Dissolving the line segments based on these two features ensures that both fields will be included in the new feature class that is created by dissolving the line segments. (I am currently using Arc 9, the method to dissolve features is slightly different in version Arc 8.3)

To dissolve the line segments using Arc Map version 9 open the Arc Toolbox in Arc Map. One the Search tab, search for Dissolve. The correct Dissolve tool is the Dissolve (Data Management Tool). Double Click on the Dissolve tool, this will bring up the dissolve menu.



In the Dissolve Menu Select the Input Feature class as WCULink and navigate to your desired output location and enter in the WCULink name. I dissolved the features based on the two fields WCUID and WCUName. Click OK.



Based on these dissolve features the resulting feature class Attribute Table looks something like this:

Attributes of WCULink_Dissolve2

OBJECTID*	Shape*	WCUID	WCUName	Shape_Length
5	Polyline	<Null>	03090102006495	3310.515126
6	Polyline	<Null>	03090102008461	6504.452329
7	Polyline	<Null>	03090102008477	186.909815
8	Polyline	1	S65-A	59300.040293
9	Polyline	2	S65-BC	162432.963427
10	Polyline	3	S65-D	47613.138278
11	Polyline	4	S65-E	39840.161214
12	Polyline	5	Lake Kissimmee	237930.071429
13	Polyline	6	C-41 AN	35927.139439
14	Polyline	7	C-41 AS	71687.635585
15	Polyline	8	C-41N	104754.992245
16	Polyline	9	C-40	53638.472961
17	Polyline	10	C-41S	42652.081954
18	Polyline	11	L-60W	21744.858527
19	Polyline	12	L-60E	14307.927063
20	Polyline	13	L-59W	28998.483733
21	Polyline	14	L-59E	80095.796377
22	Polyline	15	S-154	23853.681707
23	Polyline	16	S-133	42386.414176
24	Polyline	17	Lake Okeechobee	958449.331169
25	Polyline	18	Lake Istokpoga	77023.257453
26	Polyline	19	S-131	9703.710842
27	Polyline	20	L-49	39415.370079
28	Polyline	21	L-48	47443.855301

Record: 1 Show: All Selected Records (0 out of 28 Selected.) Options

There were a couple of line segments that were not part of a particular WCUCatchment in the Three Lakes Regions. At this point I deleted these extra line segments. Dissolving the line segments based on the two features WCUID and WCUName reduced the number of line segments from over 600 to only 28.

8. Add Appropriate Fields to meet Data Requirements

In order to match the Dissolved feature class with the WCULink feature class design, several fields must be added. In the attribute table click on **Options**, **Add Fields**. The first field added to the feature class was the field AGENCY, with a string length of 100 characters. A description of the WCULink feature class can be found in the Logical Design Document for the AHED project. All of the fields described in the document were added taking care to add the fields in the correct order and maintaining the integrity of the WCUID and WCUName from the original dissolved feature class. To keep the original values of the WCUID and WCUName a field called WCUID_1 was added, and the values calculated based on the WCUID field. Once this new fields was calculated, the old field WCUID was deleted and a new WCUID field, in the correct location, was added back into the table. The values for the new WCUID field were calculated based on the WCUID_1 field. Once these values were added into the table, the temporary field WCUID_1 was deleted. The same process was used to include the new field WCUNAME.

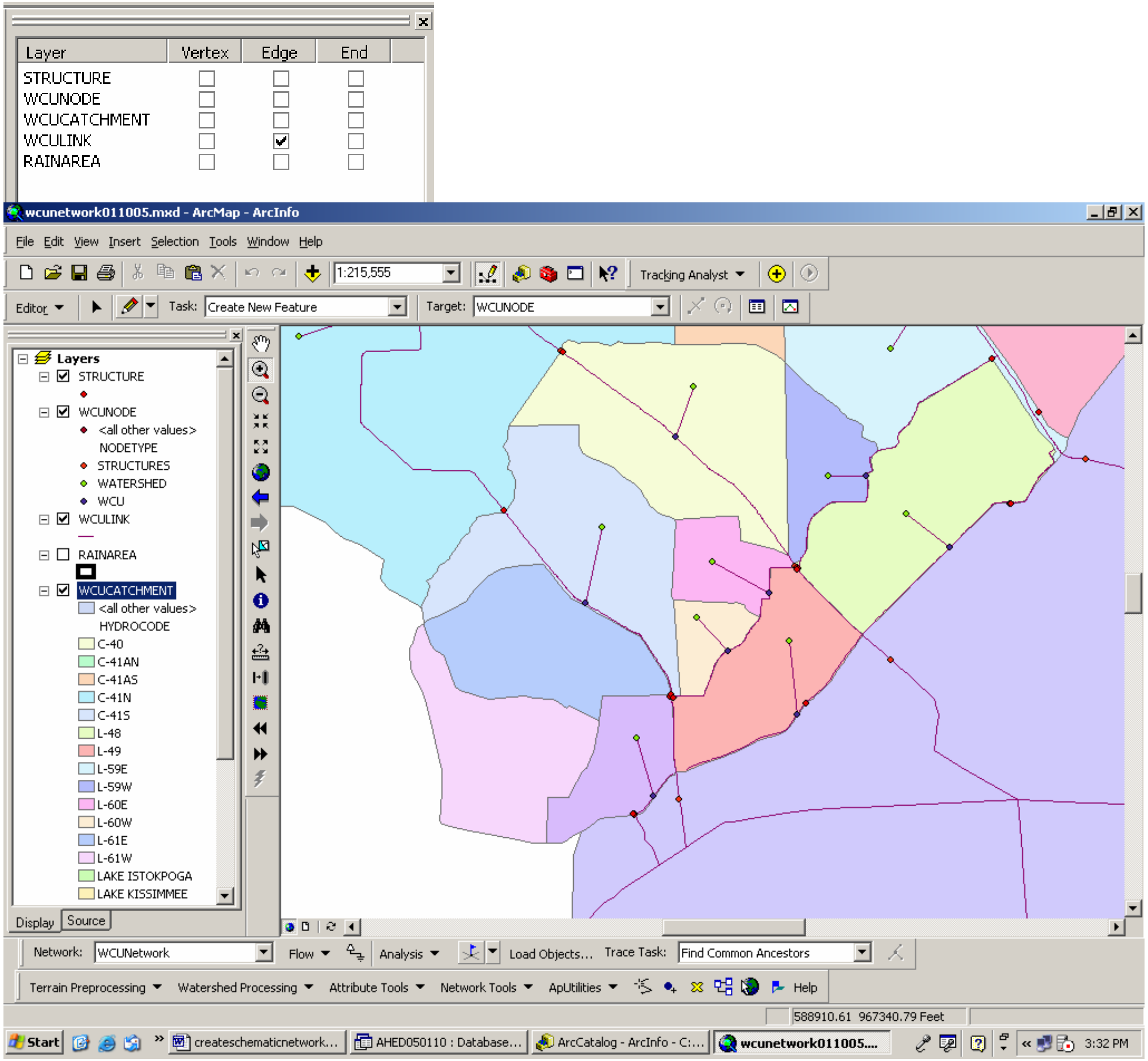
9. Add WCUNode features

Once each line segment has been created, schematic nodes can be added to the network. There are three different defined types of nodes: water control unit nodes, structures nodes, and watershed nodes. Each node type is defined in the field NODETYPE.

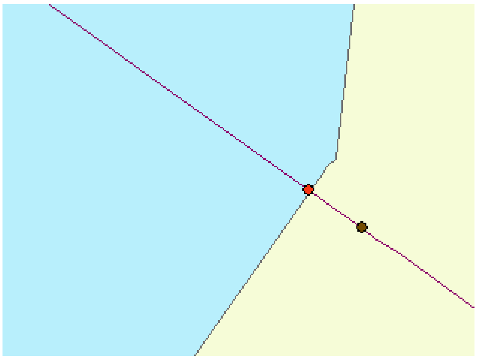
All three types of nodes have to be added into the schematic network, I have found that the watershed and water control unit nodes are the easiest ones to start with. First add in all of the watershed nodes, by using the Editor Toolbar. Start the **Editor**, select **Start Editing**. Select the task as **Create New Feature** and the target **WCUNODE**.

To add nodes, click on the drawing tool and add a new node for each watershed in the area you are working. (We have generally been adding the watershed nodes in the middle of the WCUCatchment feature.) Click Save Edits. Edit the field WCUName to include the name of the watershed and the field NODETYPE to indicate that the node is a watershed node.

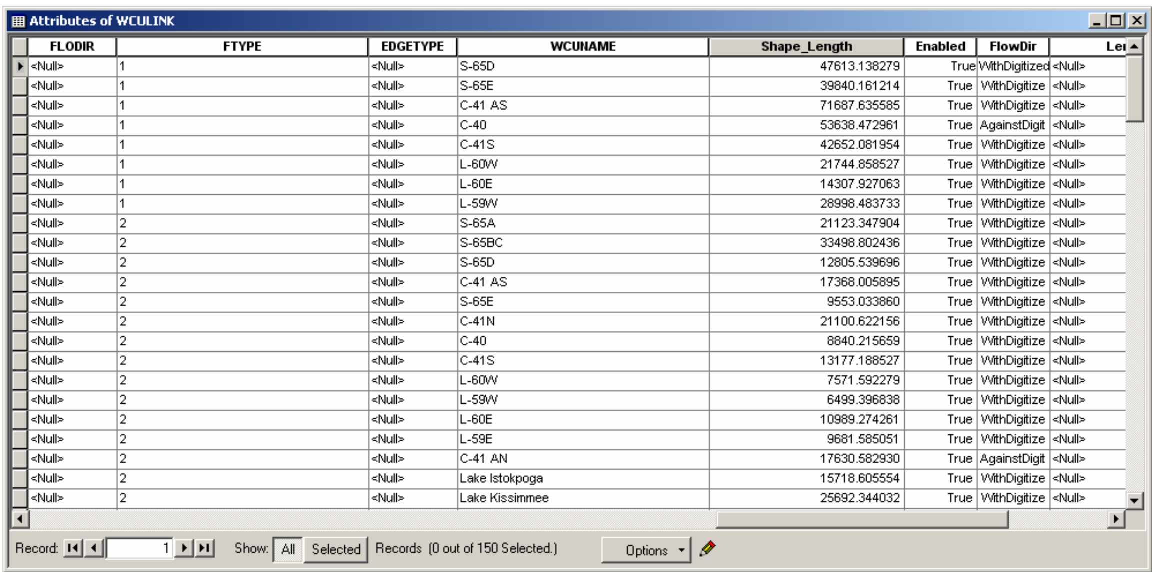
Next, add in the water control unit nodes, generally in the middle of the water control unit line segment. These node types are defined at WCU nodes. Use the Editor to select the correct node type for these nodes. Make sure to snap the Water Control Unit nodes to the WCULink line segments. To do this select **Editor**, **Snapping** and select WCULink Edge as shown below. Add in the new WCU nodes as you did previously with the watershed nodes.



The third set of nodes that needs to be added to the network is the structures nodes. These nodes define the end of a Water Control Unit. As you have done previously, add in each structures node, making sure to snap the nodes to the WCULink feature class. The location of each node should correspond to the location of each structure; however, if the structure does not lie on the WCU boundary, then the schematic node is added along the boundary of the Water Control Unit. An example of a schematic structure location is shown below; the schematic node is shown in red, and the structure node in brown.



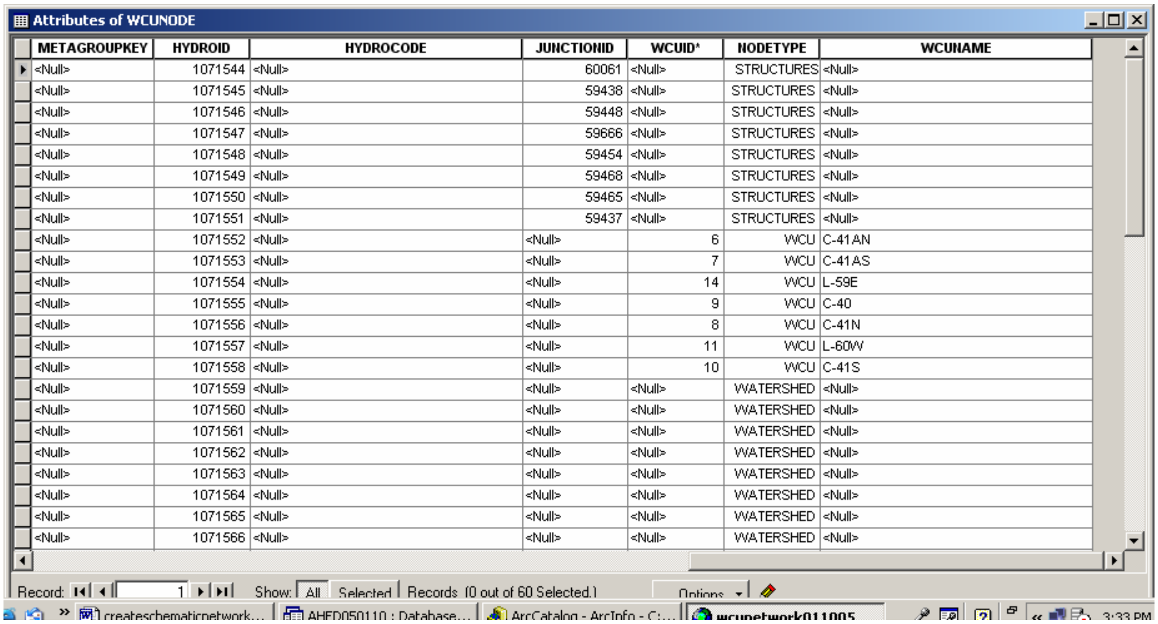
Save Edits once all of the new links have been created.



Attributes of WCULINK

FLODIR	FTYPE	EDGETYPE	WCUNAME	Shape_Length	Enabled	FlowDir	Le
<Null>	1	<Null>	S-65D	47613.138279	True	WithDigitized	<Null>
<Null>	1	<Null>	S-65E	39840.161214	True	WithDigitize	<Null>
<Null>	1	<Null>	C-41 AS	71687.635585	True	WithDigitize	<Null>
<Null>	1	<Null>	C-40	53638.472961	True	AgainstDigit	<Null>
<Null>	1	<Null>	C-41S	42652.081954	True	WithDigitize	<Null>
<Null>	1	<Null>	L-60W	21744.858527	True	WithDigitize	<Null>
<Null>	1	<Null>	L-60E	14307.927063	True	WithDigitize	<Null>
<Null>	1	<Null>	L-59W	28998.483733	True	WithDigitize	<Null>
<Null>	2	<Null>	S-65A	21123.347904	True	WithDigitize	<Null>
<Null>	2	<Null>	S-65BC	33498.802436	True	WithDigitize	<Null>
<Null>	2	<Null>	S-65D	12805.539696	True	WithDigitize	<Null>
<Null>	2	<Null>	C-41 AS	17368.005895	True	WithDigitize	<Null>
<Null>	2	<Null>	S-65E	9553.033860	True	WithDigitize	<Null>
<Null>	2	<Null>	C-41N	21100.622156	True	WithDigitize	<Null>
<Null>	2	<Null>	C-40	8840.215659	True	WithDigitize	<Null>
<Null>	2	<Null>	C-41S	13177.188527	True	WithDigitize	<Null>
<Null>	2	<Null>	L-60W	7571.592279	True	WithDigitize	<Null>
<Null>	2	<Null>	L-59W	6499.396838	True	WithDigitize	<Null>
<Null>	2	<Null>	L-60E	10989.274261	True	WithDigitize	<Null>
<Null>	2	<Null>	L-59E	9681.585051	True	WithDigitize	<Null>
<Null>	2	<Null>	C-41 AN	17630.582930	True	AgainstDigit	<Null>
<Null>	2	<Null>	Lake Istokpoga	15718.605554	True	WithDigitize	<Null>
<Null>	2	<Null>	Lake Kissimmee	25692.344032	True	WithDigitize	<Null>

Record: 1 Show: All Selected Records (0 out of 150 Selected.) Options



Attributes of WCUNODE

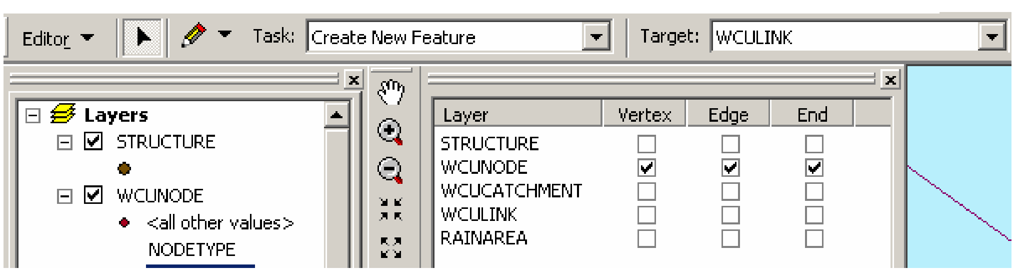
METAGROUPKEY	HYDROID	HYDROCODE	JUNCTIONID	WCUID*	NODETYPE	WCUNAME
<Null>	1071544	<Null>	60061	<Null>	STRUCTURES	<Null>
<Null>	1071545	<Null>	59438	<Null>	STRUCTURES	<Null>
<Null>	1071546	<Null>	59448	<Null>	STRUCTURES	<Null>
<Null>	1071547	<Null>	59666	<Null>	STRUCTURES	<Null>
<Null>	1071548	<Null>	59454	<Null>	STRUCTURES	<Null>
<Null>	1071549	<Null>	59468	<Null>	STRUCTURES	<Null>
<Null>	1071550	<Null>	59465	<Null>	STRUCTURES	<Null>
<Null>	1071551	<Null>	59437	<Null>	STRUCTURES	<Null>
<Null>	1071552	<Null>	<Null>	6	WCU	C-41AN
<Null>	1071553	<Null>	<Null>	7	WCU	C-41AS
<Null>	1071554	<Null>	<Null>	14	WCU	L-59E
<Null>	1071555	<Null>	<Null>	9	WCU	C-40
<Null>	1071556	<Null>	<Null>	8	WCU	C-41N
<Null>	1071557	<Null>	<Null>	11	WCU	L-60W
<Null>	1071558	<Null>	<Null>	10	WCU	C-41S
<Null>	1071559	<Null>	<Null>	<Null>	WATERSHED	<Null>
<Null>	1071560	<Null>	<Null>	<Null>	WATERSHED	<Null>
<Null>	1071561	<Null>	<Null>	<Null>	WATERSHED	<Null>
<Null>	1071562	<Null>	<Null>	<Null>	WATERSHED	<Null>
<Null>	1071563	<Null>	<Null>	<Null>	WATERSHED	<Null>
<Null>	1071564	<Null>	<Null>	<Null>	WATERSHED	<Null>
<Null>	1071565	<Null>	<Null>	<Null>	WATERSHED	<Null>
<Null>	1071566	<Null>	<Null>	<Null>	WATERSHED	<Null>

Record: 1 Show: All Selected Records (0 out of 60 Selected.) Options

10. Add Additional WCULink features

Although the majority of the WCULink features have been added to the database, there are still additional links that need to be added. These links are the links between the Watershed nodes and the WCU nodes.

To add the appropriate WCULink features make sure you are in edit mode, and that Create New Feature is selected and the target is WCULink. Select Editor, Snapping. To snap the WCULink features to the appropriate nodes select the WCUNode feature for End, Edge, and Vertex.



Use the Sketch tool to create links/line segments between all of the watershed nodes and the corresponding WCU nodes. Once you have created all of the links between these two nodes open the Attribute Table of the WCULink feature class. On all of the newly created WCULink features change the FType from a Null value to 2.

Save Edits.

Go through all of the new WCULink features and make sure that they are connected to the WCUNodes.

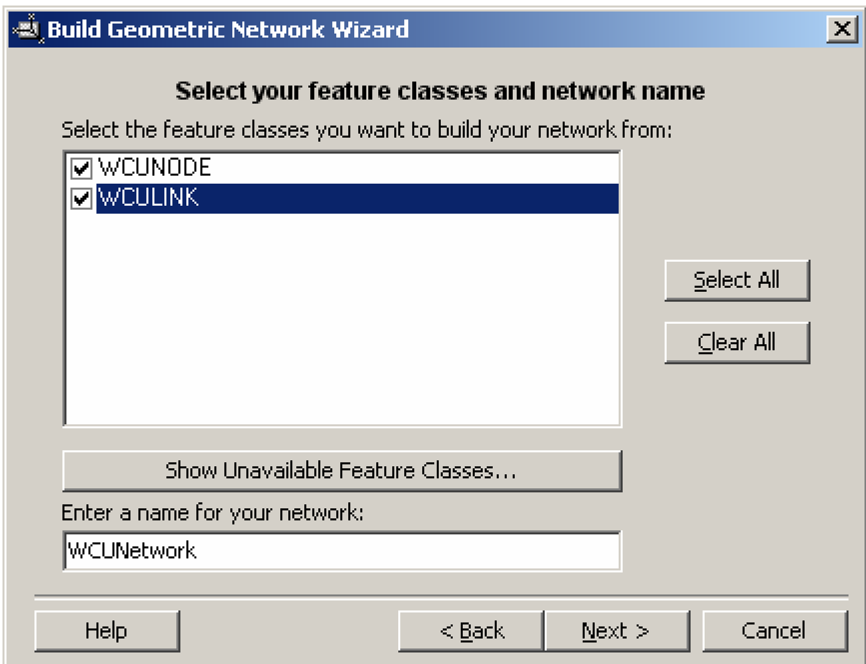
Close Arc Map.

11. Build Geometric Network

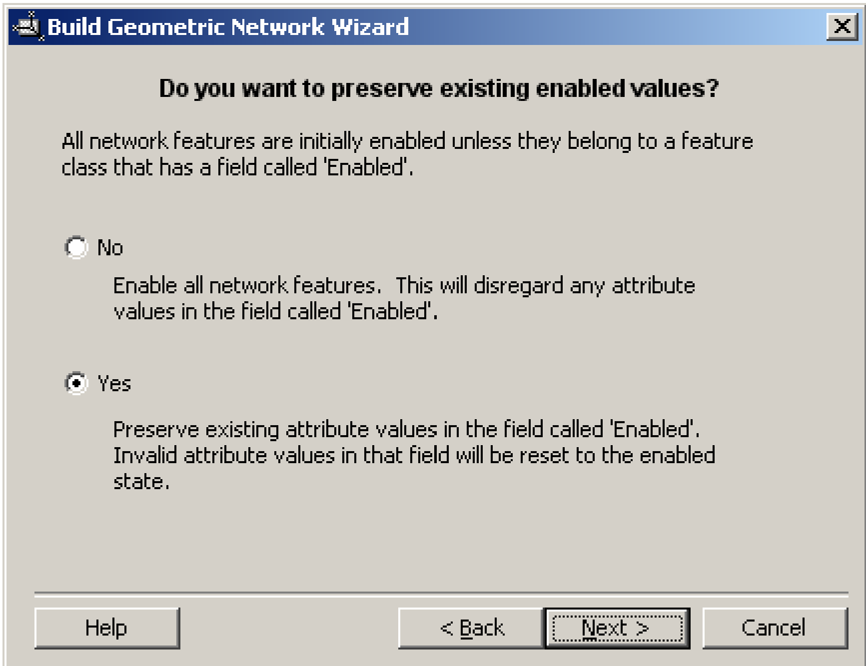
At this point we can now create the geometric network. Open Arc Catalog and navigate to the AH_ODSS feature dataset. Right click on the feature dataset and click, **New**, **Geometric Network**. This will open the Geometric Network Wizard, click **Next**.

Select **Build Geometric Network from Existing Features**. Click **Next**.

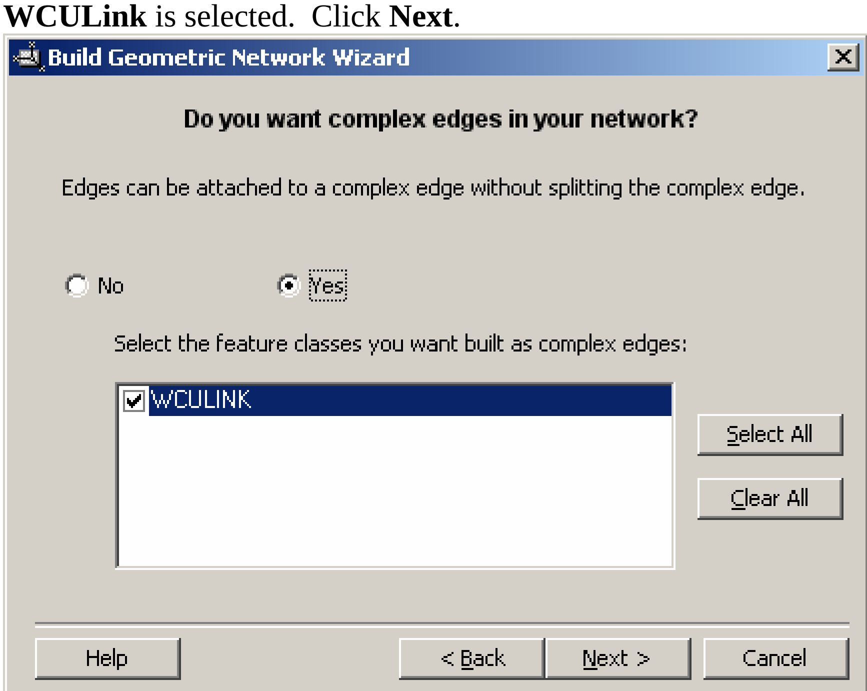
Select the feature classes WCULink and WCUNode. Enter in WCUNetwork for the network name. Click **Next**.



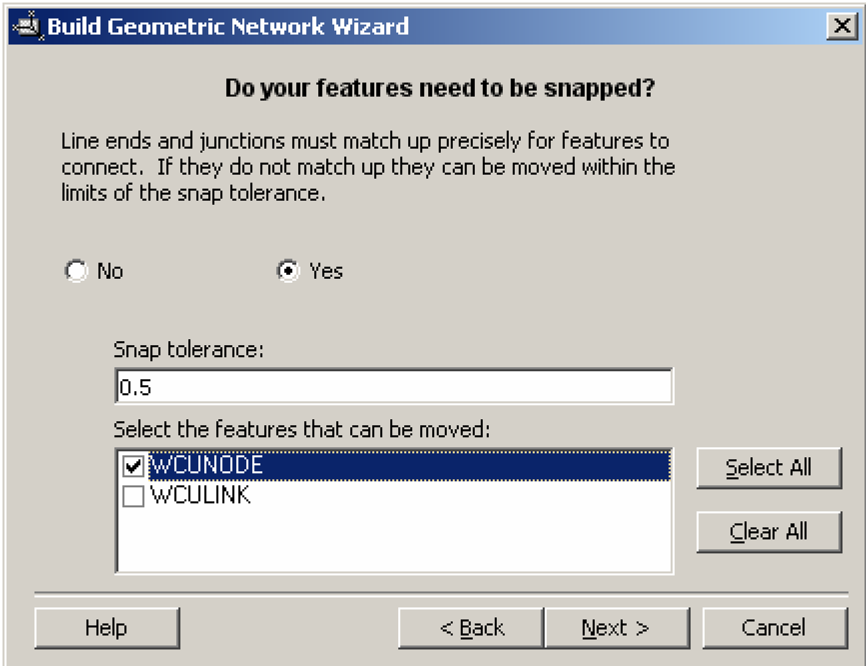
Select **Yes**. Click **Next**.



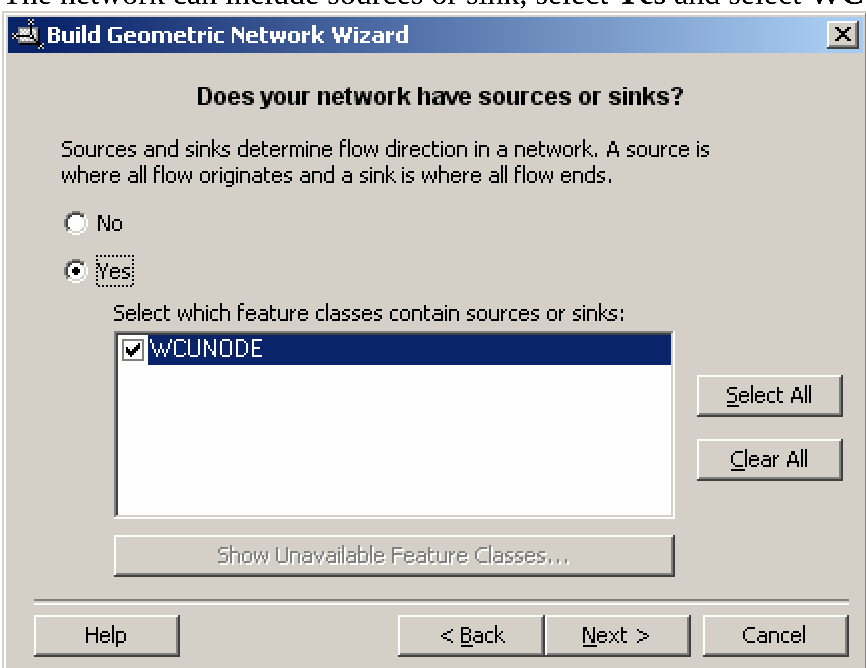
Allow for complex edges to be built in the network. Select **Yes** and make sure **WCULink** is selected. Click **Next**.



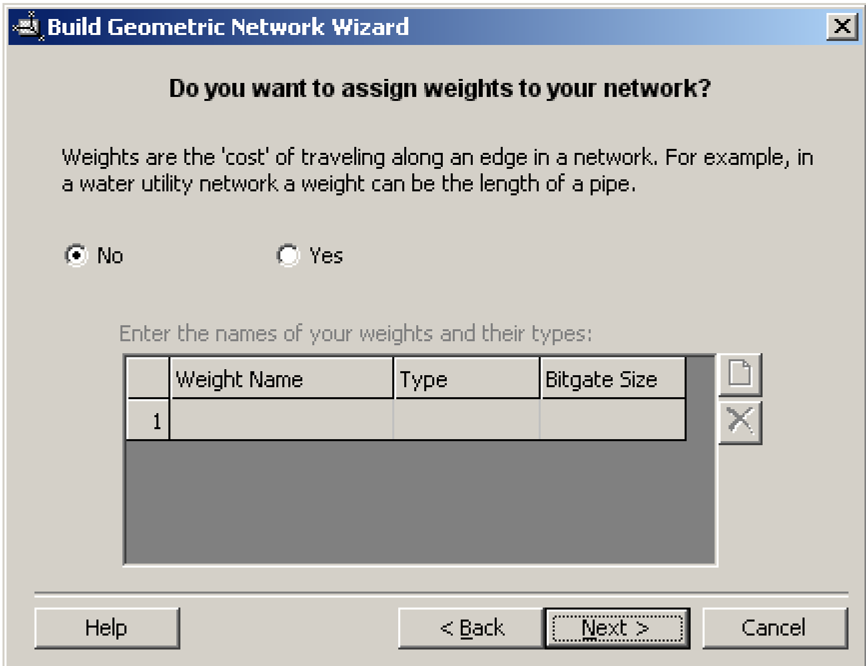
In case some of the WCUNodes are not snapped to the line work, select Yes, allow for a desired snap tolerance, I put in a snap tolerance of 0.5, and select the feature **WCUNode**. Click **Next**.



The network can include sources or sink, select **Yes** and select **WCUNode**. Click **Next**.



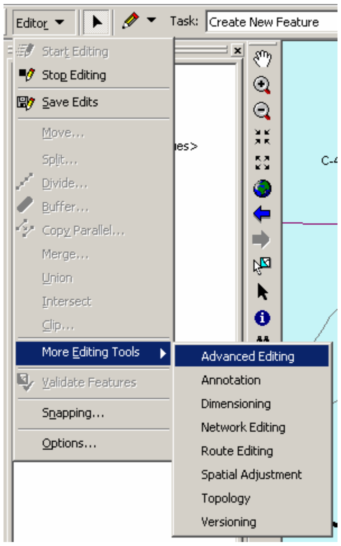
At this point there is no need to add weights to the system, select **No**. Click **Next**.



Review the data and Click **Finish**.

12. Fix Build Errors

Hopefully you will have a completed geometric network, if not an error file is created. Check the error file to determine the types of error that occurred. When I did this step I recorded the features that had errors in them, in my case they were multipart features that were not supported by the geometric network. I had to delete the geometric network and open Arc Map. In Arc Map add the feature class with the errors in it. Start the **Editor** Toolbar. Select **More Editing Tools**, **Advanced Editing**.



In the Advanced Editing Toolbar there is a tool called Explode Feature, . First select the feature you need to explode into multiple parts and then click on the Explode Tool. This will increase the number of line segments in the feature class WCULink, but all of the information stored on the single line segment will be carried

Repeat this process for all of the features that contained multipart errors.

Save Edits. **Stop Editing**.

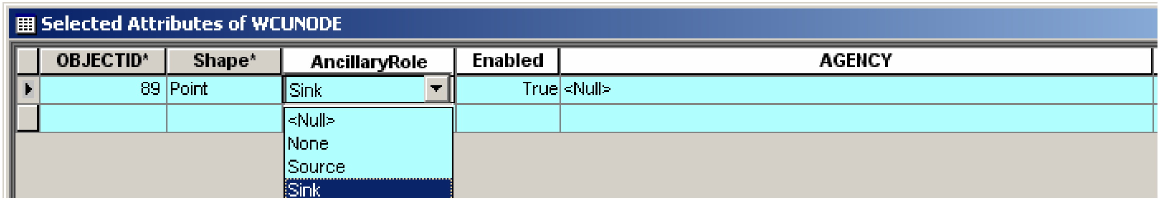
Repeat the attempt to build a geometric network as described in step 11. If build errors are produced record the errors, delete the network and edit the links and nodes until there are no errors produced when you build a geometric network.

13. Assign Flow Direction

Close Arc Catalog and open Arc Map. Load the Arc Hydro Toolbar.

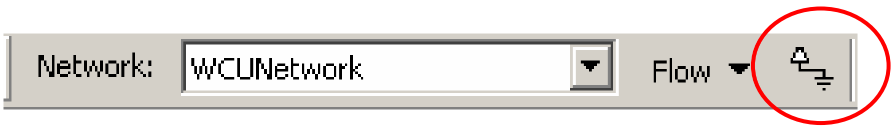
Start Editor.

Select one or more WCU type nodes as a sink, I have selected the node in the center of Lake Okeechobee as a sink node by changing the type of AncillaryRole the node plays on the network. Open the Attribute Table .



Repeat this process for any other nodes that you would like to designate as sources or sinks in the geometric network.

While still in the Editor mode click on the Set Flow Direction button to set flow directions relative to the newly assigned sources and sinks.

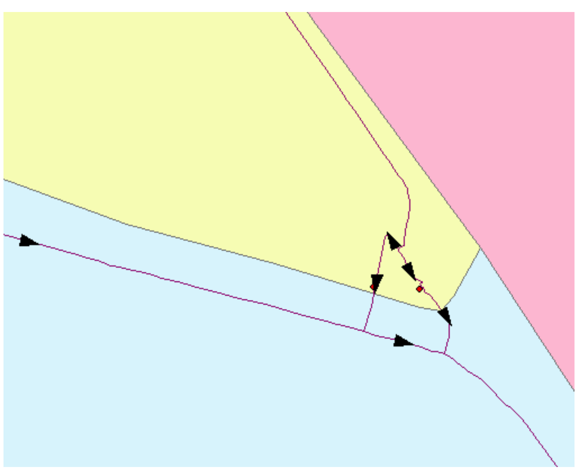


When I initially did this not all of the line segments had an initialized flow direction. This was due to two main reasons:

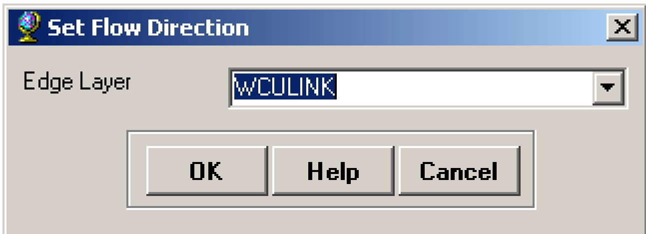
1. Line segments not connected to the network,
2. Multiple pathways for flow

To correct the first problem zoom to the line segment that is not connected to the network and use the snapping tool to snap the WCULink line segment onto another WCULink line segment. Click the Set Flow Direction button again. This should fix this type of network error.

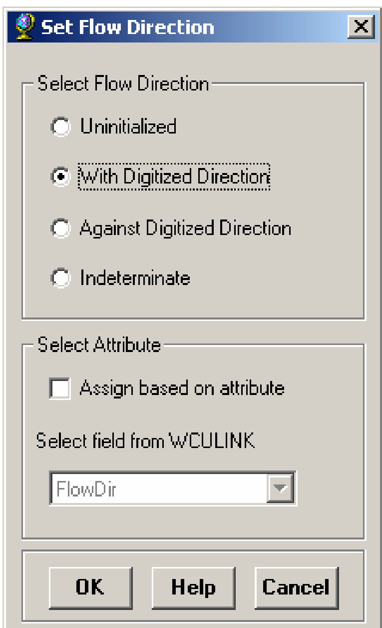
For areas in the network where there are multiple pathways the easiest way to correct the flow directions is to Select all the line segments that have not been assigned a flow direction by the Set Flow Direction function. On the Arc Hydro toolbar select Network Tools, Set Flow Direction.



Select WCULink, as shown below and Click OK.

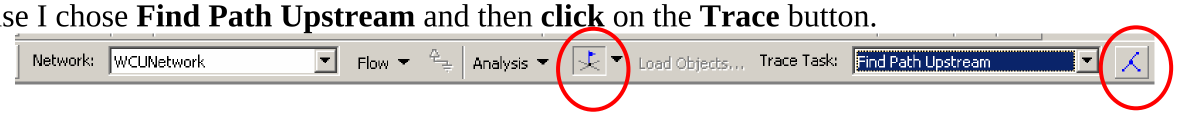


Select a flow direction to set the selected line segment to. I generally started with **With Digitized**, and if the flow direction did not match the network, then repeated the processes picking **Against Digitized**.



Once you have completed all of the flow direction changes, click **Save Edits**. Check to make sure that all of the line segments produce a continuous network by tracing upstream and downstream from a point. When I was completing the network there were small segments that did not match the overall network flow direction.

To trace upstream or downstream from a point on the Network Toolbar Select the **Flag Tool** and place the flag somewhere on the network. Select the Trace Task as desired, in this case I chose **Find Path Upstream** and then **click** on the **Trace** button.



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Vita

Alicia Diane Fogg was born on February 23, 1979, in North York, Ontario, Canada. She is the daughter of two University of Texas alumni, John Brian James Fogg and Sharon Kay Fogg. She graduated from Markville Secondary School in Markham, Ontario, Canada in 1997 and attended Northern Collegiate Institute and Vocation School in 1998 to complete her university prep courses. In 1998 she started at the University of Waterloo in Waterloo, Ontario, Canada in Environmental (Civil) Engineering where she graduated top in her class in 2003. Upon completion of her undergraduate degree she entered graduate school at the University of Texas in the fall of 2003.

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